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Journal

of

THE ROYAL AERONAUTICAL SOCIETY

DECEMBER 1955

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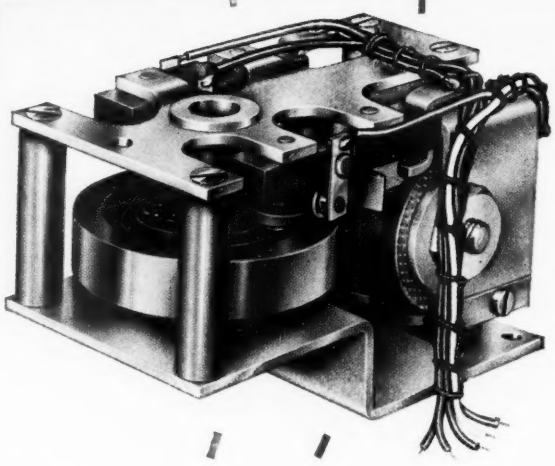

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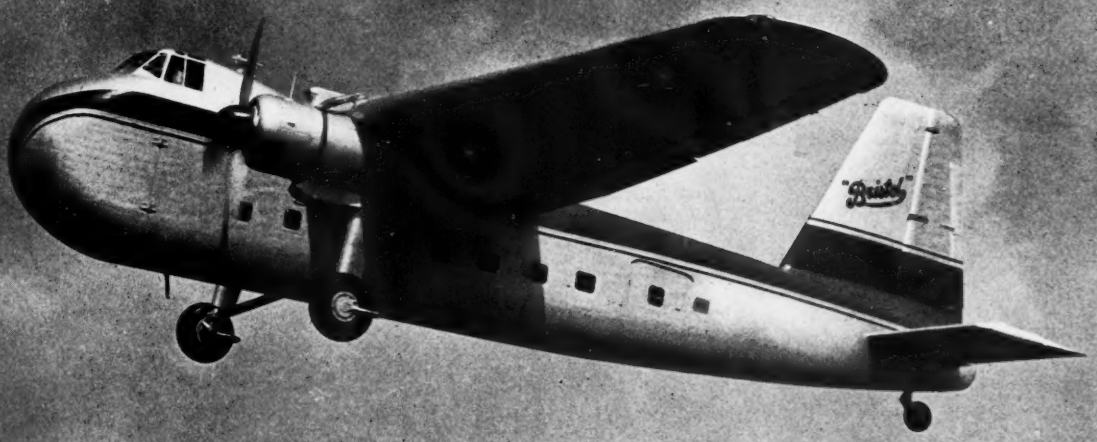

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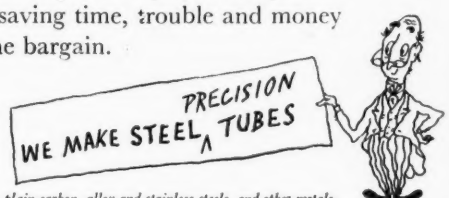

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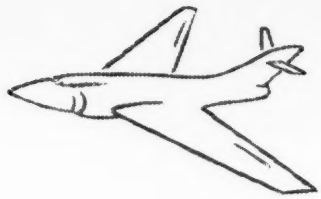

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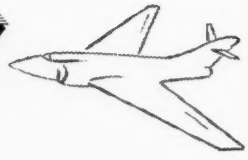

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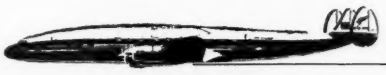

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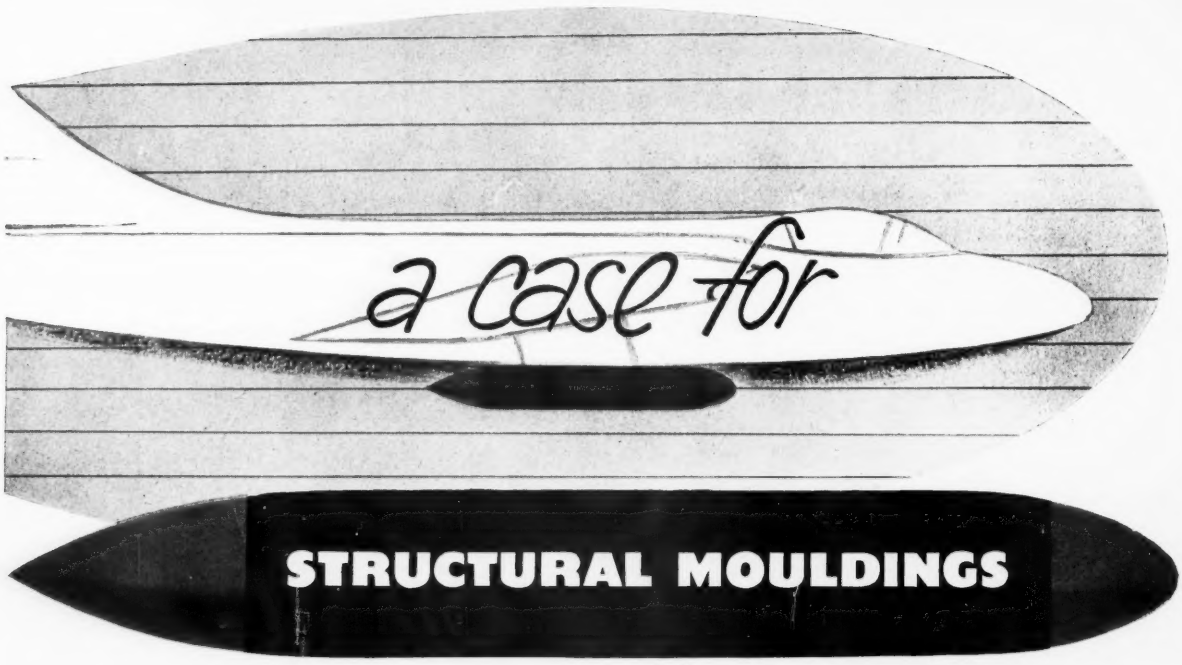

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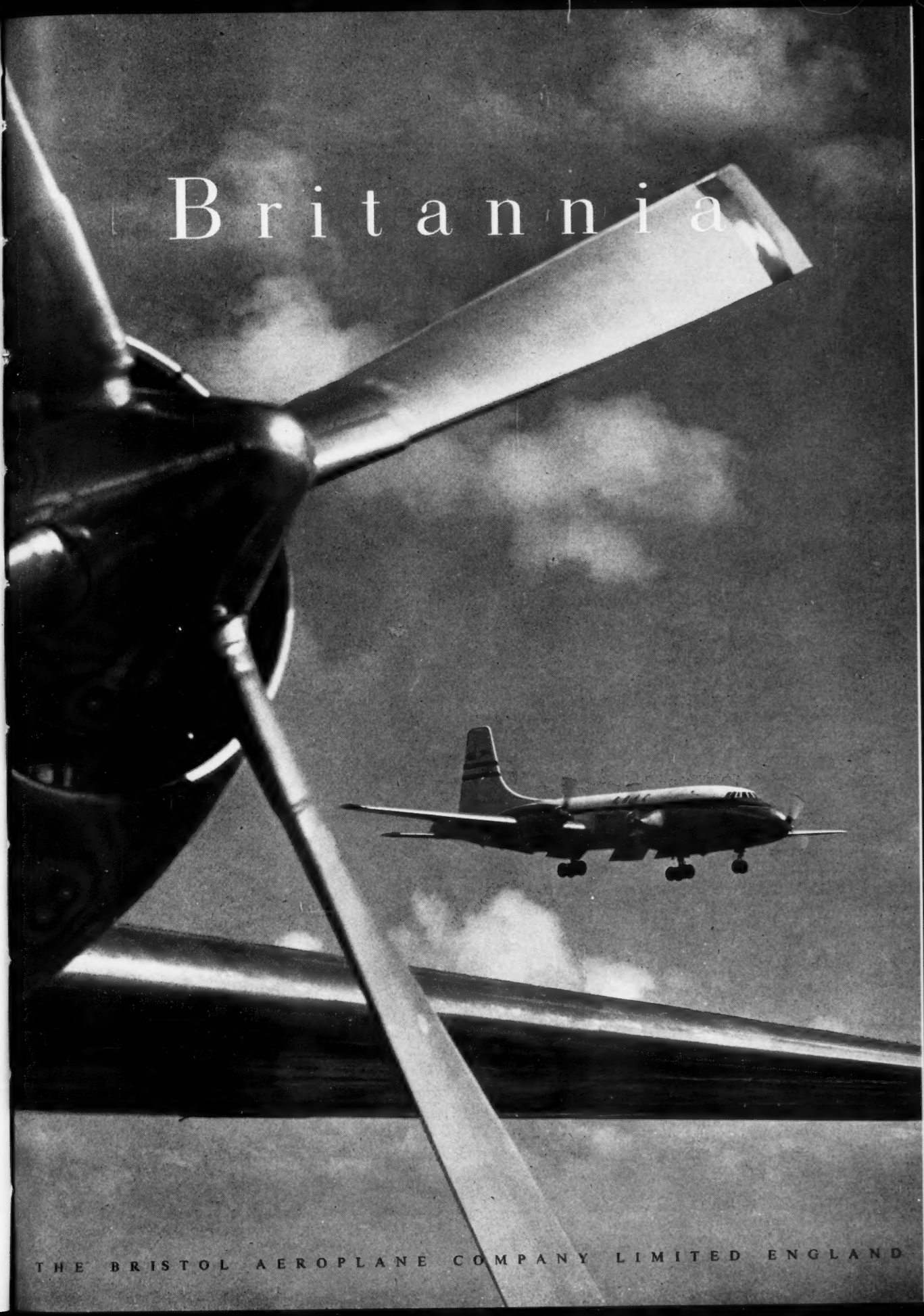
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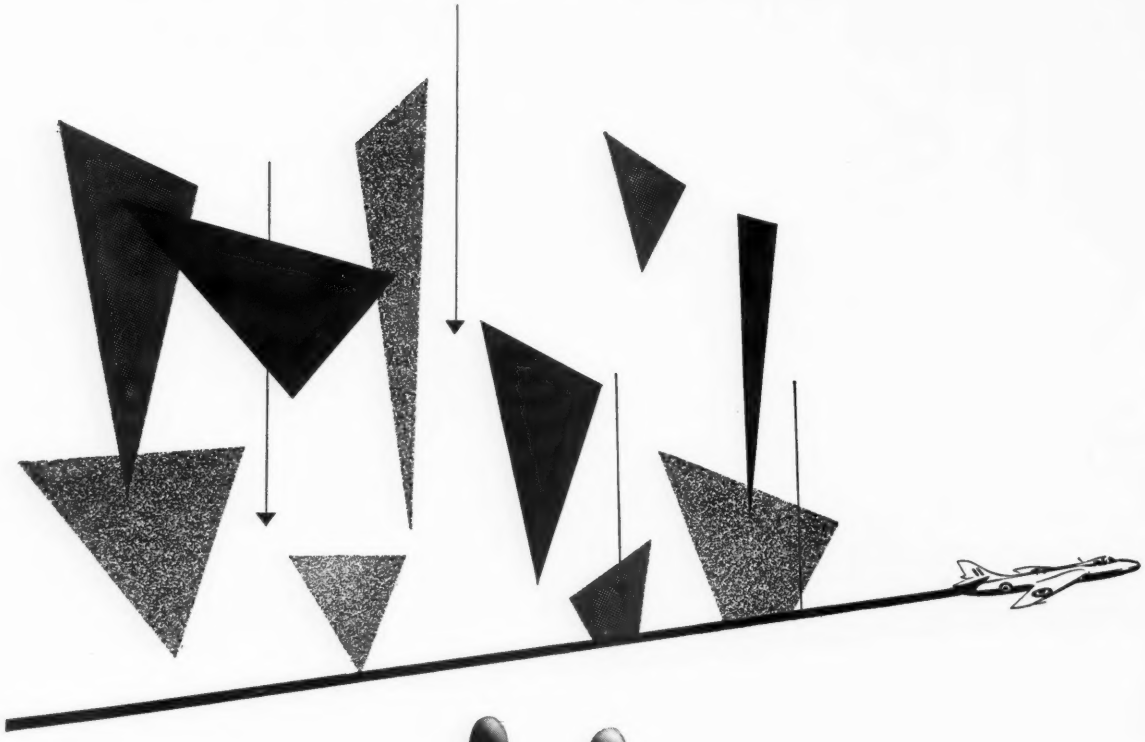

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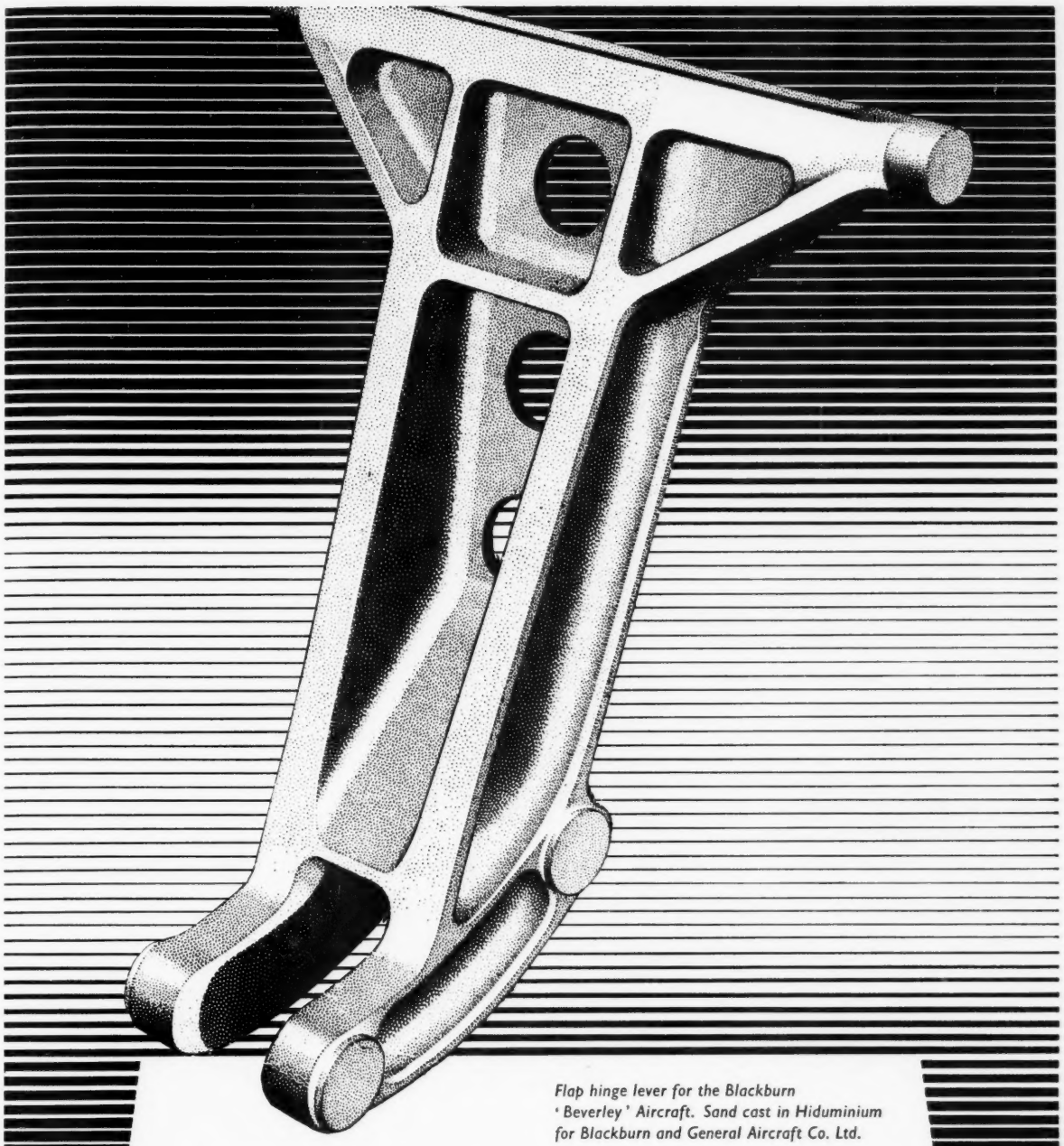

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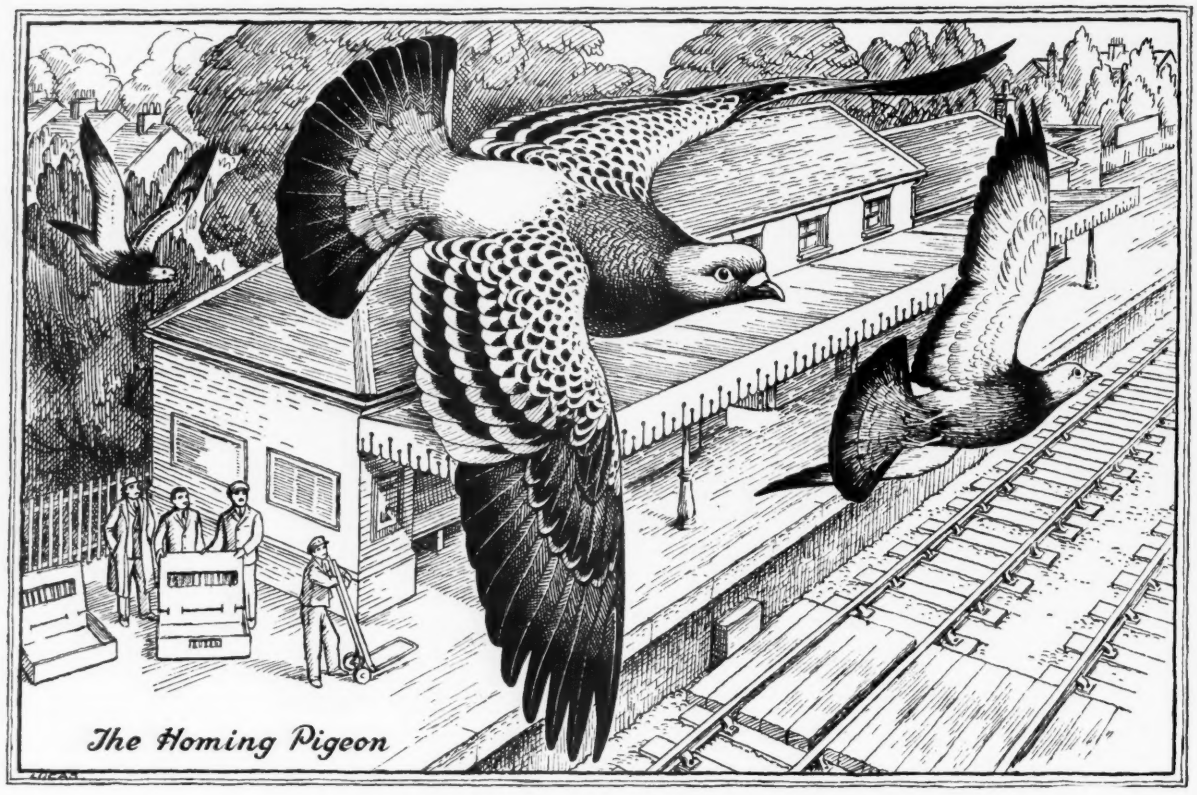
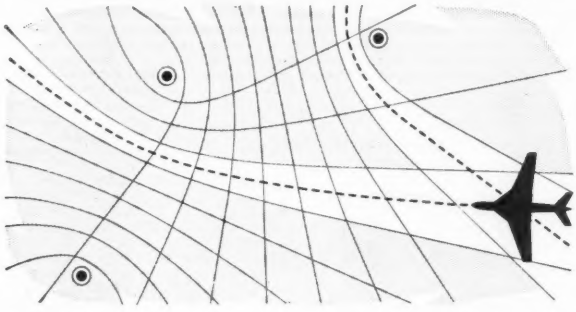


ON THE BEAM

By flying down a beam pilots can come into an airfield they cannot see and could not possibly find. With this invaluable technique man has rediscovered a gift he may once—long ago—have had : one that many creatures have in highly developed, highly efficient form.



Butterflies cross seas and make safe landfalls; the Chinook salmon swims oceans and returns, infallibly, to the very pool of the very river in which he was born ; a pair of finches divide their year, season after season, in a particular bush in an English garden and another in a North African orchard. Most astonishing of all, the homing pigeon can be taken in any direction, for any distance, and after a turn or two in the air will fly unhesitatingly straight for home.

How does the pigeon do it ? We do not know. We may never know. It is not sight, nor smell. If it is sense of direction, this must be developed to a degree of sensitive infallibility which puts it clear beyond human understanding. We can only say that —like hundreds of kinds of migratory creatures— the pigeon feels some mysterious, unmistakable pull towards home : that he senses some " radio beam " that gives him his direction.

Though we may never know the mechanics of the homing pigeon's " beam ", we imitate its effects. Landing under any but the best daylight conditions can be difficult indeed without this navigational aid we have copied from Nature.

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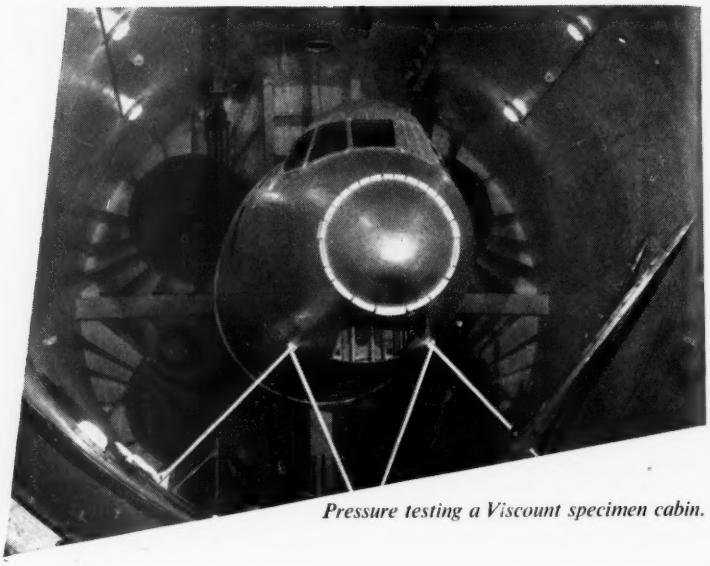

Pressure testing a Viscount specimen cabin.

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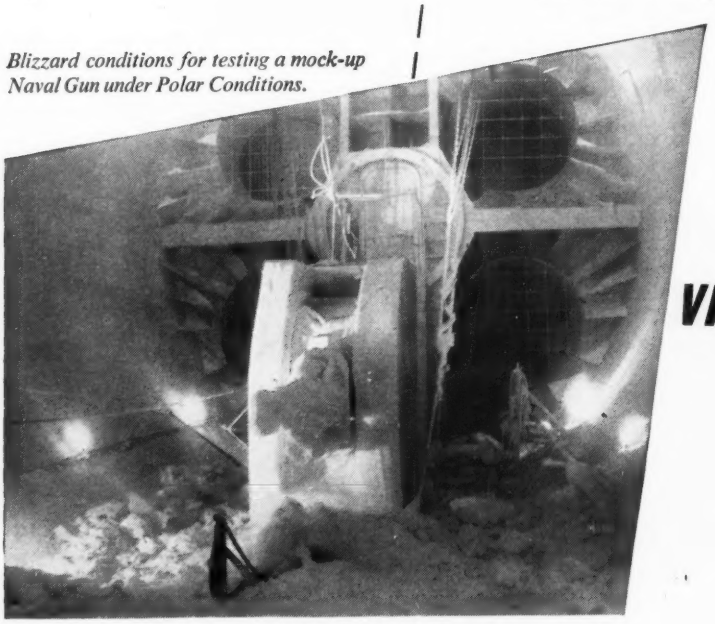
Blizzard conditions for testing a mock-up Naval Gun under Polar Conditions.



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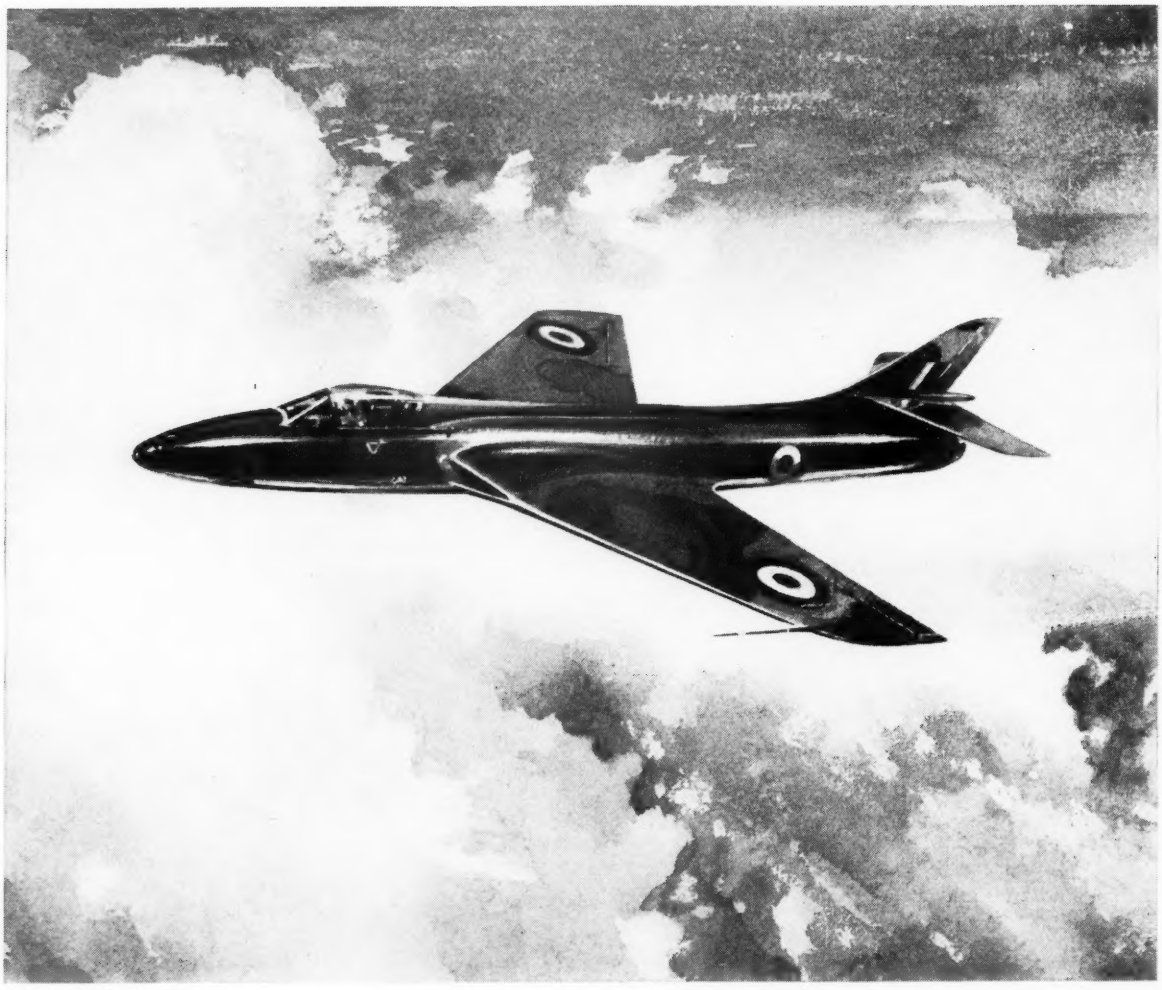

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President: Marshal of the R.A.F. VISCOUNT TRENCHARD, [G.C.B., O.M., Hon.F.R.Ae.S.
Chairman: Gp. Capt. E. E. KNOWLES, M.B.E., A.F.R.Ae.S.
Hon. Secretary: Flt. Lt. B. D. AUSTEN, A.F.R.Ae.S., Apprentice Schools, R.A.F., Halton.

HATFIELD
President: Sir GEOFFREY DE HAVILLAND, C.B.E., A.F.C., [Hon.F.R.Ae.S.
Chairman: C. T. WILKINS, O.B.E., F.R.Ae.S.
Hon. Secretary: E. J. MANN, A.R.Ae.S., de Havilland Aircraft Co. Ltd., Hatfield.

HENLOW
President: Air Commodore C. L. DANN, C.B.E., F.R.Ae.S.
Chairman: Group Captain T. G. G. HUTCHINSON, C.B.E.
Hon. Secretary: Sqn. Ldr. E. J. HOLDEN, Engineer Wing, R.A.F. Technical College, Henlow, Bedfordshire.

ISLE OF WIGHT
President: Sir ARTHUR GOUGE, Hon.F.R.Ae.S.
Chairman: H. KNOWLER, F.R.Ae.S.
Hon. Secretary: L. W. ROSENTHAL, A.F.R.Ae.S., Saunders-Roe Ltd., Osborne, E. Cowes, Isle of Wight.

LEICESTER
Chairman: F. WATKIN, A.F.R.Ae.S.
Hon. Secretary: K. B. AYERS, A.F.R.Ae.S., 10 Spinney Rise, Birstall, Leicester.

LUTON
President: Air Vice-Marshal Sir CONRAD COLLIER, K.C.B., C.B.E., A.F.R.Ae.S.
Chairman: E. N. B. BENTLEY, A.F.R.Ae.S.
Hon. Secretary: H. J. BROOKS, A.F.R.Ae.S., Hunting Percival Aircraft Ltd., Luton Airport.

MANCHESTER
President: Sir ROY H. DOBSON, C.B.E., J.P., F.R.Ae.S.
Chairman: C. E. FIELDING, O.B.E., F.R.Ae.S.
Hon. Secretary: J. A. E. WATERFALL, 56 Manor Avenue, Ashton-on-Mersey, Cheshire.

MERTHYR TYDFIL
President: C. S. GARDNER.
Chairman: J. INGRAM.
Hon. Secretary: G. M. MAGILL, A.F.R.Ae.S. Teddington Controls Ltd., Cefn Coed, nr. Merthyr Tydfil, South Wales.

PRESTON
President: Sir GEORGE H. NELSON.
Chairman: W. HARPLEY.
Hon. Secretary: E. LOVELESS, A.F.R.Ae.S., Aircraft Division, English Electric Co. Ltd., Warton Aerodrome, nr. Preston.

READING
President: Sir FREDERICK HANDLEY PAGE, C.B.E., [Hon.F.R.Ae.S.
Chairman: R. J. FENNER, A.F.R.Ae.S.
Hon. Secretary: G. H. DAVIES, Grad.R.Ae.S., Handley Page (Reading) Ltd., The Aerodrome, Woodley, Reading.

SOUTHAMPTON
Chairman: H. C. SMITH, F.R.Ae.S.
Hon. Secretary: G. T. HUDSON, A.F.R.Ae.S., Folland Aircraft Ltd., Hamble, Hants.

WEYBRIDGE
President: G. R. EDWARDS, C.B.E., F.R.Ae.S.
Chairman: H. H. GARDNER, F.R.Ae.S.
Hon. Secretary: E. G. BARBER, Vickers-Armstrongs (Aircraft) Ltd., Weybridge.

YEOVIL
President: E. C. WHEELDON.
Chairmen: D. L. HOLLIS-WILLIAMS, F.R.Ae.S., and E. W. STILL, F.R.Ae.S.
Hon. Secretary: L. A. LANSDOWN, A.F.R.Ae.S., Westland Aircraft Ltd., Yeovil.

Secretary's News Letter

December 1955.

ENCLOSED with this issue of the JOURNAL is an application form for tickets for the Reception after the Address by the President on the 12th January 1956. On that date, if I may use a metaphor from sporting parlance, the Society will be " 90 not out." Judging from the activities of 1955, continuing the metaphor, it is batting as well as ever.

The Reception will be held at the Royal Institution in Albemarle Street, and it is greatly to be hoped that there will be a goodly attendance both at the lecture and the Reception.

It is to be noted that the dress is informal. This is at the expressed desire of the President, who wishes to meet as many members as possible, especially the younger members to whom a special ticket will be issued. It is " special " inasmuch as it is at half price. I hope that many Graduates and Students under twenty-five years old, will avail themselves of this concession.

There will be talk, and eating and drinking —a buffet supper is provided—and more talk!

In the Secretary's News Letter of November last I said that I hoped that the YEAR BOOK would be issued soon. It accompanies this JOURNAL, and I hope everyone will read it thoroughly. I do not wish to comment upon it, but I should like the members of the Society to be aware that during these past months the Publications Department, headed by Mrs. Joan Bradbrooke, have acted upon Sir Winston Churchill's dicta of sweat and blood—but there were no tears. And before that the entire Technical Department spent hours on " subbing."

Let me reiterate that there are gaps in the YEAR BOOK; most of these can only be filled in with the co-operation of the members.

Soon it will be Christmas again; soon cards of goodwill and best wishes will be " shoaling " into 4 Hamilton Place, and every office will be decorated. From the staff and myself I would wish all members of the Society a very Happy Christmas with thanks for the pleasant memories of past years.

A. M. Ballantyne

Secretary

NOTICES

An annual sum of £250 is available for premium awards for papers, including Technical Notes, published in the Journal. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics

Christmas 1955

The President, Mr. N. E. Rowe, the Council and Staff of the Society wish all members at home and overseas, a Very Happy Christmas.

The Library and Offices of the Society will be closed for the Christmas Holidays from 5 p.m. on Friday 23rd December until 9 a.m. on Wednesday 28th December 1955.

Library

The Library will be closed on, Wednesday, Thursday and Friday, 14th, 15th and 16th December 1955.

News of Members

Miss F. B. Bradfield (*Fellow*) has retired from her post in the Aero. Department of the Royal Aircraft Establishment where she has been since 1918. Miss Bradfield is one of the very few women to be elected to full Fellowship of the Society.

John Bezzant (*Associate*) has left de Havilland Aircraft Co. Ltd., Portsmouth, and has taken up a post as Production Methods Engineer with Folland Aircraft Ltd.

T. E. G. Bowden (*Associate Fellow*) has recently taken up a post with Rolls-Royce Pty. of Australia Ltd. He was formerly Senior Engineer, Department of Defence Division of Aircraft, New South Wales.

M. F. Collins (*Graduate*) has recently transferred from the Design Office of Vickers-Armstrongs (Aircraft) Ltd., to the firm's Design Office at Hurn.

W. D. Douglas (*Fellow*) has retired from Harris Lebus Ltd. where he has been in charge of research work on furniture construction since leaving the R.A.E., Farnborough, in 1946.

A. Evans (*Associate Fellow*) has left The Fairey Aviation Co. Ptd. Ltd., of Australia, and taken up a post with Avro Aircraft Ltd., of Canada.

J. E. Fox (*Associate*) has left Saunders-Roe Ltd. to take up a post as an Aircraft Design Engineer with the Lockheed Aircraft Corporation in Georgia, U.S.A.

L. S. Greenland (*Associate Fellow*), Chief Designer of H. M. Hobson Ltd., has been appointed to the Board of Directors.

A. Hillier (*Associate Fellow*) was recently invested by H.E. The Italian Ambassador on behalf of the President of the Italian Republic as Commendatore of the Order of Merit.

J. A. R. Kay (*Fellow*), director of A. V. Roe & Co. Ltd., Manchester, has been appointed General Manager of the company.

D. C. Kholi (*Graduate*) has left the Aviation Division, Dunlop Rubber Co. Ltd., to join Rolls-Royce Ltd. as a Technical Assistant in the Structural Department.

P. R. Lancaster (*Graduate*) has left Rolls-Royce Ltd. to take up a post as Research Engineer at the Production Engineering Research Association, Melton, Mowbray.

R. E. Leete (*Associate Fellow*) has left British Overseas Airways Corporation and has been appointed Assistant Director of the Society of British Aircraft Constructors.

A. M. A. Majendie (*Associate Fellow*) has been appointed President of the Institution of Navigation for 1955-56.

P. G. Masefield (*Fellow*), formerly Chief Executive of British European Airways, has been appointed Managing Director of Bristol Aircraft Ltd.

Increase in Journal Subscription Rates

Because of the greatly increased costs of production and distribution the Council has decided, with much regret, that the price of the Journal must be increased.

The new rates, beginning with the January 1956 issue, will be:

Single copies—12s. 6d. each, plus 9d. postage and packing (home and abroad).

Annual subscriptions: £7 10s. 0d., plus 9s. 0d. postage and packing (home and abroad).

The 1955 rates wil be accepted for all 1956 subscriptions which are already paid, or where invoices or renewal notices have already been issued.

Orders for subscriptions for January-December 1956 Journals received up to *15th January 1956* will also be accepted at the 1955 rates but all orders for Journals received after that date will be charged at the new rates.

Honours Awarded to Members

Dr. Theodore von Karman (*Hon. Fellow*) has been awarded the Guggenheim Medal for 1955 by the Daniel Guggenheim Medal Board for his "long continued leadership in the development of aerodynamic theory and in its application to the practical problems of flight; in education in the aeronautical sciences; and in stimulating international co-operation in aeronautical research."

Royal Aeronautical Society Prize in Aeronautics

A. J. Sarnecki (Down College, Cambridge) has been awarded the R.Ae.S. Prize in Aeronautics. He is working in the Engineering Department as a Research Student.

Acoustics for Aeronautical Engineers

A one-week course on "Acoustics for Aeronautical Engineers" will be given at the University of Southampton from 15th-21st April 1956. It is intended for the increasing number of aeronautical engineers who are having to deal with acoustical problems, but have had no formal training in the subject. The syllabus includes: aerodynamic noise generation and properties of sound waves; silencing methods, and the effects of noise on people; electro-acoustic measuring techniques; and effect of noise and vibration on aircraft structures. Further details may be obtained from Mr. D. M. A. Mercer, Physics Department, The University, Southampton.

Graduates' and Students' Section—Visits

Last February, a visit was made to the Guinness Brewery and, following its success, a visit is being arranged to a Wine Cellar in Central London for the evening of Wednesday 18th January. Applications should be made to the Hon. Visits Secretary, Mr. N. K. Benson, 14 Wakering Road, Barking, Essex.

H. S. Perry (*Associate Fellow*) has been appointed Senior Mathematics Master at the Technical High School, Worthing.

W. Whitney Straight (*Companion*) has left British Overseas Airways Corporation to take up a post as Executive Vice-Chairman with Rolls-Royce Ltd., Derby.

Diary

LONDON

16th December

SECTION LECTURE.—Airships of To-day. Lord Ventry. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

20th December

SECTION LECTURE.—Recent Advances in Aircraft Adhesives. Dr. N. A. de Bruyne. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

5th January 1956

YOUNG PEOPLE'S LECTURE.—Test Flying—Current Problems and Techniques. Wing Cdr. R. P. Beamont, O.B.E., D.S.O., D.F.C. The Institution of Civil Engineers, Gt. George Street, London, S.W.1. **3 p.m.** (Tea 4.30 p.m.)

10th January

SECTION LECTURE.—Some Modern Structural Problems. Prof. W. S. Hemp. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

12th January

PRESIDENTIAL ADDRESS.—N. E. Rowe, C.B.E. The Royal Institution, 21 Albemarle Street, London, W.1. **6 p.m.** (Tea 5.30 p.m.).

RECEPTION.—7.30 - 10.00 p.m. 21 Albemarle Street, (*Application form for tickets enclosed with this* JOURNAL).

17th January

SECTION LECTURE.—Crack Detection in Aircraft Structures. Dr. W. Deck. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

18th January

GRADUATES' AND STUDENTS' SECTION.—Visit to Wine Cellar in Central London. (*See* notice).

24th January

SECTION LECTURE.—Low Consumption Jet Engines. A. A. Lombard. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

2nd February

SECTION LECTURE.—New Ideas in Plastics for Aircraft Structures. J. E. Gordon. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

9th February

SECTION LECTURE.—Propellers for Military and Civil Aircraft. L. G. Fairhurst. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

16th February

Main Lecture at Yeovil Branch.—THE FIRST HENSON AND STRINGFELLOW MEMORIAL LECTURE: Stringfellow—His Life and Work. Captain J. L. Pritchard and Dr. A. M. Ballantyne. Details in January JOURNAL.

21st February

SECTION LECTURE.—Design of Low Landing Speed Aircraft. R. C. McIntyre. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

28th February

SECTION LECTURE.—Use of Elementary Plasticity in Design. Anthony J. Barrett. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

1st March

SECTION LECTURE.—Power Plants for Supersonic Flight. Dr. E. S. Moult. The Library, 4 Hamilton Place, London, W.1. 7 p.m.

7th March

The Ninth Louis Bleriot Lecture—In Paris.—The Organisation of Aeronautical Research. E. T. Jones, C.B., O.B.E.

BRANCHES

16th December

Weybridge.—Annual Dance.

19th December

Halton.—Space Flight. J. Humphries. Branch Hut, R.A.F., Halton. 6.45 p.m.

2nd January 1956

Derby.—Annual General Meeting. Winning Ten Minute Papers. Films. Rolls-Royce Welfare Hall, Nightingale Road, Derby. 6.15 p.m.

3rd January

Belfast.—Accident Proneness. Dr. J. A. Smiley. Reception Room, Kensington Hotel, Belfast. 7 p.m.

5th January

Isle of Wight.—Noise of Jet Engines. F. B. Greatrex. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6.30 p.m.

9th January

Glasgow.—Helicopters. R. Hafner. Royal Technical College, Glasgow. 7.15 p.m.

10th January

Boscombe Down.—Fatigue: the Metallic Deathwatch Beetle. D. C. Smith. Lecture Hall, A. & A.E.E., Boscombe Down, Amesbury, Wilts. 5.45 p.m.

Bristol.—Aerodynamics and Associated Problems. R. F. Creasey. Conference Room, Filton House, Bristol Aeroplane Co. 6 p.m.

11th January

Brough.—Passengers and Freight Handling by Transport Command. Wing Cdr. P. J. George. Lecture Hall, Yorkshire Electricity Board, Ferensway, Hull. 7.30 p.m.

Chester.—Supersonic Flight. G. A. V. Tyson. The Grosvenor Hotel, Chester. 7.30 p.m.

Manchester.—Analogue and Digital Computors Applied to Aircraft Design. J. Arrowsmith. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.

Weybridge.—Brains Trust. Vickers-Armstrongs (Aircraft) Ltd., Weybridge. 6 p.m.

12th January

Cheltenham.—Liquid Springs: Progress in Design and Application. A. E. Bingham. (Originally given before the Institution of Mechanical Engineers). St. Mary's College, Cheltenham. 7.30 p.m.

17th January

Bristol.—Power Plants for Supersonic Flight. Dr. E. S. Moult. Conference Room, Filton House, Bristol Aeroplane Co. 6 p.m.

18th January

Reading and District.—Progress in Gliding. A. H. Yates. Canteen, Western Manufacturing Ltd., Reading. 6 p.m.

20th January

Birmingham.—President's Night. Birmingham Engineering Centre, Stephenson Place, Birmingham. 7.30 p.m.

Leicester.—Annual General Meeting and Film Show. Lecture Theatre, Loughborough College.

24th January

Belfast.—The Turbulent Atmosphere. Eric Hyde. Kerr Room, Kensington Hotel, Belfast. 7 p.m.

Bristol.—Aeroelastic Problems in Connection with High-Speed Flight. E. G. Broadbent. Conference Room, Filton House, Bristol Aeroplane Co. 6 p.m.

26th January

Isle of Wight.—Interplanetary Flight. A. V. Cleaver. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6.30 p.m.

Yeovil.—Patents Brains Trust. Park School, Park Road (off Princes Street), Yeovil. 7.30 p.m.

30th January

Henlow.—Lecture. W. H. Lindsey. Building No. 62, R.A.F. Technical College, Henlow. 7.30 p.m.

31st January

Belfast.—Pressing, Stretching and Bumping. L. Fromson. Reception Room, Kensington Hotel, Belfast. 7 p.m.

1st February

Gloucester.—Aircraft Fatigue. H. Giddings. The Wheatstone Hall, Brunswick Road, Gloucester. 7.30 p.m.

Weybridge.—R. K. Pierson Memorial Lecture. Vickers-Armstrongs (Aircraft) Ltd., Weybridge. 6 p.m.

2nd February

Brough.—Some Meteorological Problems of High Altitude Flight. P. J. Meade, O.B.E. Lecture Hall, Yorkshire Electricity Board, Ferensway, Hull. 7.30 p.m.

6th February

Derby.—Propeller Turbine Engines for Naval Aircraft.

W. H. Lindsey. Rolls-Royce Welfare Hall, Nightingale Road, Derby. 6.15 p.m.

7th February

Boscombe Down.—The Future of Air Power. Air Marshal Sir Robert Saundby, K.B.E., C.B., D.F.C., A.F.C. Lecture Hall, A. & A.E.E., Boscombe Down. 5.45 p.m.

8th February

Chester.—Future Car Developments. The Grosvenor Hotel, Chester. 7.30 p.m.

Manchester.—The Artificial Stabilisation of Modern Aircraft. Dr. K. H. Doetsch. Reynolds Hall, College of Technology, Manchester. 7.30 p.m.

10th February

Brough.—Annual Dinner Dance. Jacksons Ltd., Hull.

Glasgow.—First Pilcher Memorial Lecture. I. R. Liddell. Royal Technical College, Glasgow. 7.15 p.m.

13th February

Henlow.—Annual General Meeting. Building No. 62, R.A.F. Technical College, Henlow. 7.30 p.m.

14th February

Bristol.—Aerial Photography. Charles E. Brown. Conference Room, Filton House, Bristol Aeroplane Co. Ltd. 6 p.m.

15th February

Coventry.—Lecture. E. P. Hawthorn. The Wine Lodge, Coventry. 7.30 p.m.

Reading and District.—Lecture and Film Show. Guided Weapons. Sqn. Ldr. R. E. W. Harland. Western Manufacturing Ltd. Canteen, Reading. 6 p.m.

16th February

Isle of Wight.—Operation of Turbo-Propeller Aircraft. P. G. Masefield. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6.30 p.m.

Yeovil.—MAIN LECTURE: First Henson and Stringfellow Memorial Lecture: Stringfellow—His Life and Work. Captain J. L. Pritchard and Dr. A. M. Ballantyne. Details in January JOURNAL.

21st February

Belfast.—The New London Airport. R. F. Bulstrode. Kerr Room, Kensington Hotel, Belfast. 7 p.m.

22nd February

Weybridge.—Training and Research in the Field of Aircraft Production. Professor J. V. Connolly. Vickers-Armstrongs (Aircraft) Ltd., Weybridge. 6 p.m.

23rd February

Cheltenham.—The Investigation of Flutter by Flight Tests. H. G. Peacock. St. Mary's College, Cheltenham. 7.30 p.m.

ANNUAL SUBSCRIPTIONS

Members are reminded that their annual subscriptions become due on 1st January 1956. The rates are:—

Fellows	..	..	..	..	5	5	0	4 4 0
Associate Fellows	..	..	..	..	4	4	0	3 3 0
*Associates	..	..	..	..	3	3	0	3 3 0
Graduates (aged under 26)	..			..	2	2	0	2 2 0
Graduates (aged 26 and over)	..			..	2	12	6	2 12 6
Students (aged under 21)	..			..	1	1	0	1 1 0
Students (aged 21 and over)	..			..	1	11	6	1 11 6
Companions	..	..	..	..	3	3	0	3 3 0
Founder Members	..	..	..	..	2	2	0	2 2 0

* Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the JOURNAL, and in this case his subscription will be reduced by £1 1s. 0d. to £2 2s. 0d.

It will avaid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership. Remittances should be made payable to the Royal Aeronautical Society.

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Roy George Adolphus
George Barr (*from Associate*)
Jabez Arthur George Beadle (*from Associate*)
Eric John Catchpole (*from Graduate*)
Prabhu Datt Chopra
George Frederick Gilmore (*from Graduate*)
Derek Lionel Hand (*from Student*)
William Risbee Heald (*from Graduate*)
Shankar Lal (*from Graduate*)
Monroe A. Maller
Adam Merton (*from Graduate*)
John Leslie Milne (*from Graduate*)
James Parker (*from Associate*)
Jack Steele Parker
Herman Sholom Pearlman (*from Graduate*)
James Deyo Redding
Ronald Albert James Regan
John William Richardson
James William Ritchie (*from Graduate*)
Charles John Street (*from Graduate*)
Edward Rupert Tyndale-Biscoe
Ronald Charles Wakeford (*from Graduate*)

Associates

Ernest George Barber
David Anthony Brooks
George William Fredrick Collins
George Frederick Miller (*from Student*)
Eric Paton
Arthur James Quigley
Norman Riley
John Septimus William Sladden
William Paul White
Edward Stanley Frederick Wright

Graduates

Clifford Ernest Allen
Anthony Lionel Blackman
Burjor Sorabji Cooper (*from Student*)
Edward Michael Cowburn
John David Duncan
Arthur Michael Hyde Dunn
John Robert Gilbert
Geoffrey Edwin Higginbottom
David George Jacobs
Peter Stanley Jaffray (*from Student*)
James Colin Lewis
Allan John Noon (*from Student*)
Theodor Opatowski
Kenneth George Page
Eric James Preston
James Arthur Prettyman
Anthony Douglas Radbone
Akella Kameswara Rao
Saul Reshelbach
Janis O. A. Stankevics
Michael Gabriel Sherry
John Douglas Vachal
John Geoffrey Mayfield Williams
Ernest Arthur Winn

Students

Richard John Aitchison
John Douglas Ward Croasdell
David James Green
Derek Charles Hayward
Lawrence William Everett Johnston
Bryan Mackay Little
Anthony Brian Maasz
John Michael Mortimer
Anthony Phillip Neave Potts
Robin Herrington Ryder
Arnold Frederick Schofield
Kenneth Staniforth
Alan Gerald Treasure

Companions

Derek Goodman
Ernest Alexander Madden

JOURNAL BINDING

Permanent Binding

The new prices for permanent binding of Journals are:

1955 Volume (including packing and postage) £1 0s. 0d.
Previous Volumes (including packing and postage) .. .. £1 1s. 6d.

Journals, with a note of the name and address of the sender, should be sent direct to The Lewes Press, Friars Walk, Lewes, Sussex, and the remittance to the Secretary at the Offices of the Society.

Self-Binder Cases

Self-Binder cases of the "Easibind" type to hold 12 Journals (cost 11s. 6d. each) are available from the offices of the Society.

The Journal of the Royal Aeronautical Society

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 59 DECEMBER 1955 NUMBER 540

ROBERT BLACKBURN *Honorary Fellow*

26th March 1885 - 10th September 1955

ON 21st DECEMBER 1953, Robert Blackburn replied to the toast, at a dinner given in the Guildhall, Kingston-upon-Hull, of "The Pioneers of Aviation." He spoke as a pioneer himself, and, as a Yorkshireman, proudly claimed that it was a Yorkshireman, Sir George Cayley, who first laid down the basic principles of flight.

When Robert Blackburn died in September there died a great Yorkshireman, with all the solid qualities of one, kindliness, generosity, warmth of heart and that simple *understanding* sincerity which is rare. He was friendly to all whom he met and retained, throughout his life, the friends he made in his younger days.

I knew Robert Blackburn nearly forty years and many, too, of those who worked closely with him over the years, years of great hopes, of great disappointments, when an assured belief, as Robert Blackburn had, in the course one was taking was an immense asset in aviation. Behind his easy friendliness, however, Robert Blackburn had the Yorkshire obstinacy which did not let him be easily swayed. He inspired the loyalty and affection and team spirit of a Yorkshire cricket captain. Many of those present at the memorial service in the flight shed at Brough must have been deeply stirred by the moving tribute paid to him by the many who had served him.

When, in 1954, his fellow manufacturers in the aeronautical industry presented him with a silver salver bearing their signatures, it was inscribed "A token of esteem and affection." Only a few months earlier sixty-one of the senior members of the firm, none with less than 25 years service, had also signed a silver salver to present to him "as a token of their affection."

Robert Blackburn indeed inspired affection and it is by that quality he will long be remembered.

He joined the Society in 1911 as a Founder Member and was made an Honorary Fellow in 1950. He served on the Council from 1932 to 1935 and 1937 to 1943. I well remember that last year of his on the Council, for it was in July 1943 that the Society was offered a unique collection of aeronautical medals, some 300 in all, dating over the period 1714 to 1941.

This astonishing collection included three medals commemorating the Montgolfier balloon ascents of 1783; the first ascent of Lunardi in London, in 1784; the first ascent of James Sadler, the earliest English aeronaut; medals commemorating the balloons used in the siege of Paris, 1870-71; the dirigibles of Giffard, Zeppelin, Parseval, the R101 and others, and Picard's stratosphere balloon of 1931.

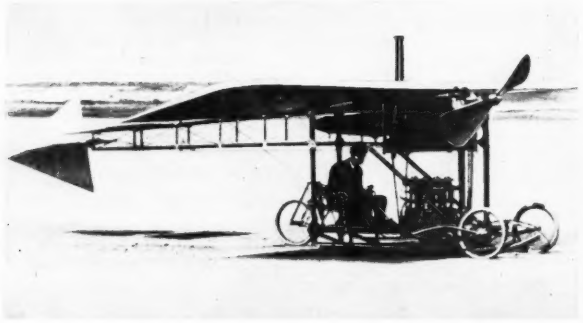
Celebrating heavier-than-air flights, the medals include Bleriot's flight across the Channel, 1909; Paulhan's flight, London to Manchester, of 1910; Pegoud's looping the loop flights; Lindburgh's New York to Paris flight of 1927; Hinkler's, London to Australia in 16 days, in 1928; Balbo's flight from Italy to America and back in 1933, leading a flight of 24 seaplanes; Amelia Earhart's flights, and many more high lights of aeronautical history.

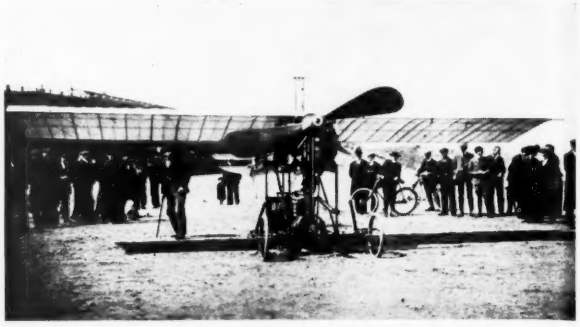
Here was an opportunity for the Society to acquire an historical collection which I believed should be seized quickly, for I knew that they might go to America, and the opportunity would not recur. But the price was close on £500!

The Council appointed a small committee to consider how the money could be found. When the Council meeting was over, Robert Blackburn followed me into my room.

"You are unhappy," he said. "I think we should have decided to buy in any case. See what you can get them for and I will give you a cheque for the amount."

The following is taken from a note recorded in the next Council Minutes:





Robert Blackburn's first monoplane—on the sands at Saltburn, 1909. In the photograph on the left, Mr. Blackburn is in the pilot's seat.

"The Secretary reported that the set of aeronautical medals mentioned in Paragraph 9 of the last Minutes had been acquired for the Society at a cost of £470 by an anonymous donor, who did not wish any announcement of his name to be made."

I have before me, as I write, a personal letter from Robert Blackburn, written a week before that Council meeting, one which he avoided attending. "On the subject of the donor," he writes, "do please let this drop. I was only anxious when the subject was raised, that the Society should not miss them."

That was like him. He was always an altruistic giver, and no announcement of this great gift to the Society has hitherto been made.

Robert Blackburn, two years ago, recalled that he was working in a civil engineering consultant's firm in Rouen (after taking an Honours degree in engineering at Leeds University), when he first saw Wilbur Wright flying in France. What he saw fired his imagination.

"I realised that the aviation 'bug' was well and truly in my blood ... I approached my employer before he had time to approach me, sacked myself and returned to Paris."

There, in a single top-floor room of a *pension*, he designed his first machine, as a monoplane. With the aid of two mechanics the monoplane was built in a garage in Leeds, fitted with a 35 h.p. Green engine and taken to the sands at Saltburn in April 1909. The engine and radiator, petrol tank and himself, as pilot, were all well beneath the wings, for he believed in a low centre of gravity for increasing stability.

There were no flying instructors. The only way to learn to fly was to get into the aeroplane and then up in the air with the hope one didn't get wings as the aeroplane lost them. Robert Blackburn got up in the air all right, made an exhilarating turn and side-slipped, with a pendulum effect, into the sands.

He began designing a new machine immediately, with a different centre of gravity. It proved very successful. It was on this machine that that great pilot B. C. Hucks learnt to fly, and, joining Robert Blackburn, gave an astonishing series of flying demonstrations in 1911.

One of Blackburn's pilots was Hubert Oxley who, with a passenger, was killed pulling out of a dive. Robert Blackburn must have been one of the earliest aeroplane designers to draw attention to the danger of pulling out of a nose dive. In January 1912 he wrote, in a letter to *Aeronautics*, "You will quite understand that when making one of these steep descents and suddenly flattening the machine out, the strain must be enormous .... there is a limit to which such descents should be made, since the velocity at the end of the dive will be so enormous that no machine could possibly stand it."

In 1912 Robert Blackburn designed his single-seater military monoplane, with an 80 h.p. Le Rhone engine. Many members of the Society will have seen it flying at the Society's Garden Parties in 1950-53. These early Blackburn aircraft were fine examples of engineering practice.

This is not the place to enter into the later history of the Blackburn and General Aircraft Company. I quote, however, from the end of his speech when replying to the toast of the Pioneers of Aviation.

"I cannot close," he said, "without saying how much the progress of the Blackburn Company has been bound up with the loyalty, co-operation and team spirit of the staff. To have 274 members of our Company who have given over 21 years of faithful service is a measure of that spirit."

He himself gave over forty years to that Company, and there were present with him, when he spoke, some, who, to quote his own words, "of my little skilled labour force who would willingly work day and night to complete an urgent job. They were a splendid lot, full of spirit and enthusiasm, and in spite of no wages being forthcoming some Fridays, they stuck to the ship."

They and many others who knew Robert Blackburn, have lost a friend.

"In every friend we lose a part of ourselves, and the best part." J.L.P.

The Eleventh British Commonwealth and Empire Lecture

The Growth of Aeronautical Research in Canada During the Post-War Decade

by

J. J. GREEN, M.B.E., Ph.D., B.Sc., A.R.C.S., D.I.C., F.I.A.S., F.C.A.I., F.R.Ae.S.
(Defence Research Member, Canadian Joint Staff, Washington)

The Eleventh British Commonwealth and Empire Lecture was given before the Society by Dr. J. J. Green, M.B.E., B.Sc., A.R.C.S., D.I.C., F.I.A.S., F.C.A.I., F.R.Ae.S., on 6th October 1955 at the Royal Institution, Albemarle Street, London, W.1, and was presided over by Mr. N. E. Rowe, C.B.E., F.R.Ae.S., President of the Society.

Mr. Rowe: Before calling on the Lecturer he had a telegram to read from the Canadian Aeronautical Institute: "The Canadian Aeronautical Institute sends greetings to the Royal Aeronautical Society on the occasion of the presentation of the British Commonwealth and Empire Lecture by Dr. J. J. Green, Past-President of the Institute." He was sure they were all very glad to have that telegram.

The Eleventh British Commonwealth and Empire Lecture was one of their three named Lectures, and was of comparatively recent institution. It was decided on in 1945, the idea having developed from a suggestion of Mr. George Dowty, now Past-President of the Society, and the original intention was that this Lecture should treat mainly of civil aviation, although in the course of time the scope had widened and tonight they were having a lecture which dealt mainly with scientific matter.

The Lecture was devised to form a focus for the aeronautical problems of the Commonwealth and Empire and he thought that it had done this exremely well. It had attracted a sequence of eminent aeronautical men, operators, engineers, administrators, and they all remembered in the most vivid way the significant and stimulating Lecture which was given in 1954 by H.R.H. The Duke of Edinburgh.

Their Lecturer this evening was a distinguished aeronautical scientist. He was born in Portsmouth, England, and studied at the Royal College of Science, of the University of London, where he obtained an Honours Degree and also an Honours Diploma of his College. He continued his studies under Professor, now Sir Leonard, Bairstow, and obtained the Ph.D. Degree of London University and the Diploma of the Imperial College. Dr. Green then went to Canada to work on aeronautical research under Mr. Parkin of the National Research Council. He was appointed Chief Research Engineer of the Royal Canadian Air Force in 1943. He became Aeronautical Research Engineer to the Canadian Air Transport Board after the War and was appointed to the Defence Research Board in 1949. In September 1955 he was appointed the representative of that body on the Canadian Joint Staff in Washington.

Dr. Green had been an enthusiastic member of the aeronautical community for many years. He was an old friend of the Society, having become a Graduate in 1929 and a Fellow in 1948. He had done a great service for Aeronautics in Canada, having been one of the most active members in promoting the Canadian Aeronautical Institute, of which he was the first President.

He thought that it was most appropriate at this time that they should have as their Lecturer a member of one of the great countries of the community of the Commonwealth. Canada was a great and growing country. It had, without doubt, vast potential in its natural resources and it had great strategic importance now and for many years to come. It was therefore, he thought, extremely good to have a Canadian give the Lecture.

"An' if the Warld upon improvements fa'
The times may come she'll need nae roads ava;
For wha wad creep like snails upo' the yird,
Gif they might sail the air like ony bird."

ANDREW SCOTT (1826)

Historical

With the exception, possibly, of the detective thriller most stories are best enjoyed by starting at the beginning. My story is no exception and, if I am to give you some feeling for the accomplishments in aeronautical research in my Country during the past ten years, I must refer briefly to what had been done already in Canada during the earlier years of this century.

Canada's first wind tunnel was built in 1902 at Rothesay, New Brunswick, by W. Rupert Turnbull and it was here that aeronautical research in Canada had its birth. A Fellow of the Royal Aeronautical Society and an Honorary Fellow of the Canadian Aeronautical Institute, Dr. Turnbull won the bronze medal of the Society in 1911 and at the time of his death in 1954, at the age of 84, he was maintaining his interest in aviation and studying the art of bird flight. The results of his

wind tunnel studies of aerofoils, in which he was seeking automatic stability, were published in the "Physical Review" in 1907.

For the study of propellers in axial motion he built himself a 300 ft. track, with a little carriage to carry the propeller and its driving motor. He published three papers, one on "The Efficiency of Aerial Propellers" in the "Scientific American" and two papers in the Journal of this Society on "The Laws of Airscrews." After the First World War he designed a controllable pitch propeller which was successfully tested at Camp Borden by the R.C.A.F. He sold his patent rights to the Curtiss-Wright Company and from these the Curtiss electric propeller was developed.

Aeronautical development in Canada began about the same time, also in the Maritime Provinces. At Baddeck, Nova Scotia, Alexander Graham Bell was experimenting with novel designs of kites from which, by the application of power, he hoped to achieve flight at the least possible risk of human life. He was greatly interested in the work done by Professor Langley who in 1894 visited Baddeck to witness some of Dr. Bell's own experiments. Two years later Dr. Bell saw a trial flight of Langley's "Aerodrome." The sight of this steam-powered model traversing the sky impressed him enormously. In his own words, "Encouraged and stimulated by this remarkable exhibition of success, I quietly continued my experiments in my Nova Scotia Laboratory in the hope that I, too, might be able to contribute something of value to the world's knowledge of this important subject."

In 1907 Glenn Curtiss, whose light gasoline engines had earned him a reputation, was invited to Baddeck to advise Dr. Bell on the application of power to his tetrahedral kites. Two young Canadians, J. A. D. McCurdy and F. W. "Casey" Baldwin, were invited to consult with Bell on the structural details. From this meeting, the Aerial Experiment Association was formed and four successful aircraft were built between 1908 and 1909. The first flight of "Red Wing" on 12th March, 1908, at Hammondsport, N.Y., by F. W. Baldwin is claimed as the first flight by a British subject, while McCurdy's flight at Baddeck on 23rd February 1909, in the "Silver Dart" is claimed as the first flight within the Empire. This group of development engineers were the first to employ ailerons for lateral control. Mr. McCurdy tells how he was explaining his method of lateral control by little wings to a French pioneer who, comprehending, exclaimed "Ah! ailerons," and the name stuck.

The first Canadian University to take a serious interest in aeronautics was Toronto, which established an aerodynamic research laboratory in 1917 at the instigation of Mr. J. H. Parkin who was then on the engineering teaching staff. The University recognised that aviation would play a part in the development of Canada and at the same time that Canada would impose on air transportation unique operating conditions. In 1918 the University constructed its first wind tunnel, a 4 ft. N.P.L.-type with a speed of 37 m.p.h. This was replaced in 1923 by a more efficient tunnel of the same size working section but having a wind speed of 60 m.p.h.

These University facilities were used for training and research and also for testing models of aircraft under development by the Canadian Aircraft Industry. The researches were mostly of an engineering nature and were concerned with aircraft problems, such as the interference between wings and fuselages, the relative efficiencies of various wing tips, the downwash behind wings, the aerodynamic effects of wing taper and the influence of thick wings in biplane arrangements.

During these years a Canadian company bearing the illustrious name of Vickers designed a number of aircraft well-remembered in Canada but with names which must sound strange to your ears, the "Vigil" and the "Velos" and the flying boats "Vedette," "Varuna," "Vanessa," "Vancouver" and "Vista." Models of these aircraft were all tested in the Toronto University wind tunnel before being built and flown. Mr. B. S. Shenstone wrote a very fine thesis based on an exhaustive analysis of the flight stability of the popular and successful flying boat, the "Vedette." This single-engined machine was used by the R.C.A.F. for forestry patrol and aerial photography.

On 7th February, 1920, the first meeting took place of the Associate Air Research Committee, which was created by the National Research Council at the request of the Canadian Air Board (forerunner of the R.C.A.F.). Its first task was to survey the university facilities which might be available for aeronautical research purposes. They were very meagre; the professors were all carrying a heavy teaching load and funds were scarce. Nevertheless, the Committee was able to sponsor a number of projects at the universities on behalf of the Air Board and those other Government Departments responsible for meteorological services, topographical survey and forestry. Among the subjects listed by the Committee in 1920 for special attention were photography as applied to topographical survey, experimental and theoretical studies of aeroplane stability, air navigation problems, especially as regards the use of directional wireless, propulsion and the possibilities of variable pitch propellers and the physiological effects of flying. Many of these subjects did receive attention in the ten years that followed. Turnbull's controllable pitch propeller, although several years in advance of its time, was completed and ground-tested in 1923. Loss of the propeller in a fire delayed the air tests until 1927.

At Alberta University, Professor C. A. Robb tackled the problems of aero engines at low temperatures. Over a number of winters he conducted experiments on engine operation, with special reference to starting difficulties and the effect of temperature on lubrication and cooling. Professor L. V. King at McGill University undertook pioneer work on hot wire anemometers for the measurement of low air velocities. Professor Bronson at Dalhousie University began the calibration of instruments at low temperature and Mr. Stanley Smith at Alberta investigated new materials and construction for the diaphragms of barographs. Mr. Parkin

at Toronto investigated the effect of ski landing gear on aircraft performance and stability. McGill University undertook to study the snow friction on runners, and elsewhere the behaviour of rubber shock cord and the strength of structural components at low temperature were given attention.

In 1929 the Government authorised the construction of aeronautical laboratories by the National Research Council. These included a 9 ft. open jet wind tunnel with a maximum speed of 230 ft./sec., a model testing basin some 400 ft. long, an engine testing laboratory and later, an aircraft instrument section and a fuel and lubricants laboratory. During the years of the depression that followed, aviation activity in Canada struggled against economic difficulties and the new laboratories devoted their major efforts to assisting in the solution of the operational problems encountered by the R.C.A.F. and the civil aircraft carriers. Extensive work was done on aircraft skis to improve their aerodynamic characteristics and their sliding performance on various types of snow surface. The engine laboratory undertook pioneer work on water injection as a means for boosting the take-off power of piston engines and also continued to grapple with the ever-present problem of engine starting at low temperature. In 1935 the study of aircraft icing was begun in a serious way. The first experiments were concerned with keeping propellers free of ice and we conceived the idea that the right way to do this was by electrical heating.

In 1939, with international tension mounting, new and expanded aeronautical laboratories[1] were designed by the N.R.C. to serve the anticipated needs of the R.C.A.F. and industry. A slightly larger wind tunnel with double the speed of the 9 ft. tunnel was built and a modern spinning tunnel was provided. A new model basin was added with greater length and width and a modern engine laboratory was constructed. Two important new laboratories were included, an aircraft structures and a low temperature laboratory. New and improved fuel and lubricant and aircraft instrument laboratories were also provided.

When it was decided that the major role of the R.C.A.F. in Canada would be air crew training, it became obvious that the primary task of the new research facilities would be, again, the solution of operational problems to keep the training aircraft flying. Among the dozens of tasks I might cite a few. Strength tests were undertaken of the Cornell aircraft, a number of which had suffered structural failures in the air. The Harvard structure was also tested, since at times over-exuberant trainees had returned with excessive permanent buckling of the upper wing skin. The high accident rate due to ground looping of Harvard and Fleet Finch aircraft sparked other investigations which led to modifications that satisfactorily reduced the accident rates. A vibration analysis of the Cessna Crane twin-engined trainer revealed the existence of tail flutter as the cause of a series of hitherto unexplained accidents.

FIGURE 1. Aerial view of Aeronautical Laboratories, National Research Council, as they appeared in 1945.

In the expectation of a shortage of aluminium the technique of fabricating complete aircraft and components in moulded plywood was thoroughly investigated; a pilot plant was set up and many components were made for static test, weathering and flight tests.

A very smart streamlined ski was designed for Sir Sydney Camm's famous Hurricane but it was too late to be used in Norway which, if I remember rightly, was the initial reason for this job. Fairey Battles were used for bombing and gunnery training in Canada and several modifications were made to them which necessitated various tests in the wind tunnel.

Low temperature was a constant source of problems for the laboratory, particularly with the intensive flying programme of the British Commonwealth Air Training Plan. The engine laboratory and the gasoline and oil laboratory inherited most of these jobs.

Looking back on this period, there was here and there a modest contribution to basic knowledge. A multitude of small jobs, mostly uninspiring and unspectacular, were done under pressure and urgency and they scarcely make interesting history. Each in its way contributed to the war effort and if they added but little to general knowledge, they at least enhanced the experience and competence of the staff[2].

The Post-War Facilities

When the 1939-45 War ended there was naturally an abrupt decrease in the scale of flying operations in Canada and a corresponding reduction in the demands on the laboratories. The National Research Council now had a well-experienced and mature staff of fairly adequate size equipped with facilities which had proved to be well suited to the war needs. Here was a splendid opportunity to direct their capabilities into fundamental research channels to make a worthwhile contribution to aeronautical development in the broadest sense. This policy was accepted and it was agreed that the emphasis would be on research, although the laboratories would continue, wherever possible, to assist the Industry which had, during the war years, also grown and matured.

The Government had decided towards the end of the war, that Canada would participate actively in the gas turbine field and as an initial step it created Turbo Research Limited, a Crown Company, to implement this policy. Shortly after the end of hostilities the

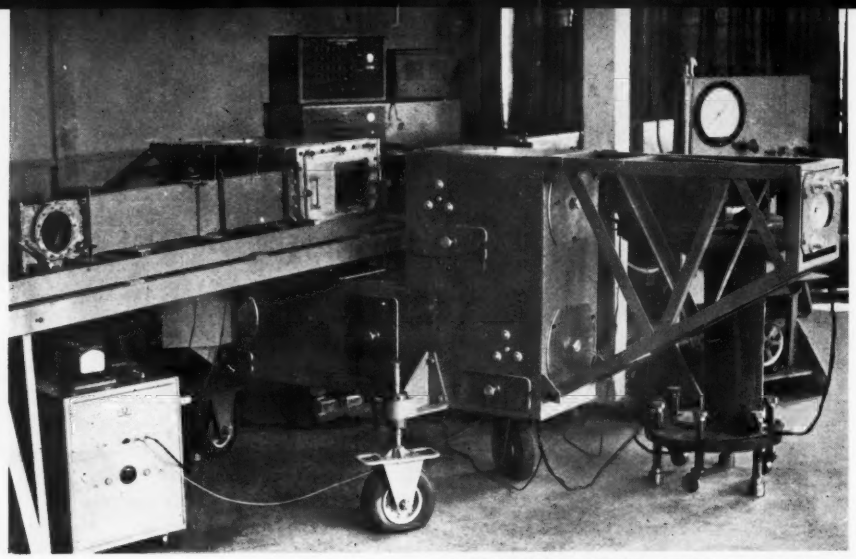


FIGURE 2. The 2 in. × 7 in. shock tube and Mach-Zehnder Interferometer, University of Toronto, Institute of Aerophysics.

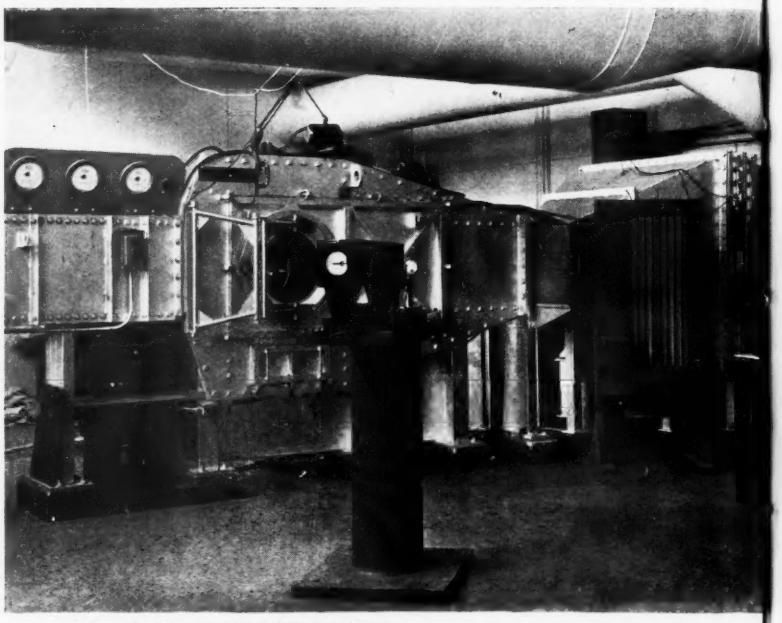


FIGURE 3. The test section of the U.T.I.A. 16 in. × 16 in. supersonic wind tunnel, showing the Schlieren system camera.

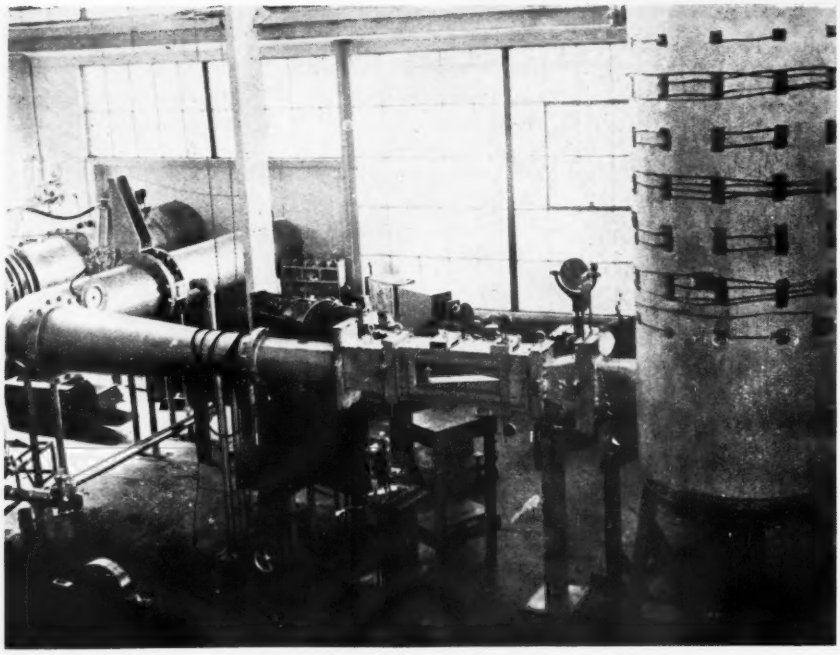


FIGURE 4. The U.T.I.A. small supersonic wind tunnel installation, showing the 5 in. × 5 in. hypersonic test section in use.

Government took another forward step with the decision to introduce, for the first time, the development of military aircraft in Canada. This task was assigned to A. V. Roe Canada Limited, a new Company with an old but distinguished name, which also assumed the gas turbine development responsibilities of Turbo Research Limited. The research functions of this Company were given to the National Research Council, and Turbo Research Ltd. disappeared from the scene. These events indicated that, in addition to its basic research activities, the National Research Council would inevitably be called upon to give extensive assistance to the important engine and airframe developments to which we had set our hands.

The wartime developments in aviation and the new emphasis on gas dynamics made us aware of a necessity for additional facilities to meet the demands of industry for basic knowledge. The N.R.C. began immediately to plan this expansion of its equipment (Fig. 1). At the same time it was realised that scientists and engineers with advanced training would be needed and that steps should be taken to provide such training in the universities. Both Toronto and McGill Universities took action to meet this situation.

Aerodynamics

In January, 1947, Dr. G. N. Patterson came to the University of Toronto as Professor of Aerodynamics, having recently completed studies in the new field of stationary and non-stationary supersonic flow. He undertook to train graduate students in this subject and to arrange for suitable research projects. In the next two years a number of able graduate students did good work with a 2 in. by 7 in. shock tube[3] (Fig. 2) and a 1 in. by 1 in. intermittent blowdown supersonic wind tunnel.

In 1949 the Defence Research Board, which had been created two years earlier to be responsible for the application of science to defence matters, entered into an agreement with the University of Toronto for the construction and operation of an Institute of Aerophysics, with Dr. Patterson as its Director. The establishment was to train scientific personnel for research and development in the basic physics of gases, applied aerodynamics and ballistics, with special emphasis on supersonic flight. It was also to engage in aerophysics research and to develop practical applications therefrom. Design work started at once[4] on a 16 in. by 16 in. supersonic wind tunnel of the closed jet, intermittent type in which air flows from a specially constructed moisture-proofed room (capacity 36,000 cu. ft.) through the tunnel and into a 40-ft. diameter evacuated sphere. The tunnel (Fig. 3), which has a running time of about 25 seconds, has been operated up to a Mach number of 2·92.

The vacuum and air supply of this tunnel has been arranged to permit operation of a 5 in. by 7 in. or, by interchange of test sections, a 5 in. by 5 in. wind tunnel (Fig. 4). The former is a supersonic facility for the $M=1{\cdot}5$ to $4{\cdot}0$ range and the latter is a hypersonic facility for the range $M=5$ and above. An air inlet heater is employed to prevent air condensation over the speed range of this equipment.

The 2 in. by 7 in. shock tube mentioned earlier has been a most useful research tool during the past seven years[5, 6]. It consists of four steel sections giving a total length of 11 feet when assembled. The compression chamber can be pressurised to 4 atmospheres and the expansion chamber evacuated to less than 1 mm. Hg. A schlieren optical system used initially has been replaced by a large field Mach-Zehnder interferometer. Shock wave velocity is obtained by a schlieren-photo-cell system which provides electrical trigger pulses from the passage of the shock wave. Transient pressures are measured by piezo-electric gauges. A 3 in. by 3 in. wave interaction tube[7] is used for the study of interactions between plane waves in one dimension. It is composed of a number of sections and a special 30 in. viewing section. A high and a low pressure chamber of any desired length can be provided and the provision of two diaphragm stations enables complicated interactions to be set up. A 12 in. diameter schlieren beam and a rotating drum camera are used to obtain x, t plane photographs of the flow.

Recently a 2 in. by 2 in. strong-shock tube of 24 ft. length has been constructed for the study of shock waves at Mach numbers up to 20 (Fig. 5). Explosive mixtures of hydrogen and oxygen are used in the high pressure chamber to initiate the strong shocks. The diaphragm between the high and low pressure chambers is of brass, scribed to control its rupturing characteristics.

This year a low density tunnel for the study of slip and free molecule flow has been provided (Figs. 6 and 7). The tunnel is continuous in operation, with an open

FIGURE 5. The U.T.I.A. strong-shock tube. The surge chamber and spectrograph are in the foreground. The pressure vessel containing a square shock tube section is in the background.

jet test section (maximum diameter 5 in.) and vacuum pump drive. It will operate from subsonic speeds up to a Mach number of 5·0. The test section static pressure may be varied between 0·001 and 0·07 mm. Hg. and the mean free path in the jet will range from a minimum of 0·002 in. up to 2·0 in. To reduce the extremely thick boundary layer growth on the nozzle walls, which is characteristic of low density operation, provision is made for slotted wall nozzles with boundary layer suction, thereby keeping boundary layer thickness and hence the nozzle Mach number, constant over a range of operating pressures. Even with suction the boundary layer will fill the channel at pressures less than 10 microns, so that the tunnel may only be operated subsonically at these very low pressures. Instrumentation includes a traversing mechanism for moving pressure probes or models inside the test section by remote control, static pressure measuring gauges and micromanometers for impact and inlet stagnation pressure measurement.

The old R.A.E. type open-return tunnel of the University of Toronto was replaced in 1952 by a conventional return type, closed section subsonic tunnel with a 9 to 1 contraction ratio. The new tunnel has a top speed of 160 m.p.h. in a 32 in. by 48 in. test section for a power expenditure of 60 h.p.. It is used for training and, to an increasing extent, for research by graduate students.

The National Research Council has also added a high-speed aerodynamics laboratory to its facilities[8], the first supersonic tunnel being placed in operation in March 1951. This has a 10 in. by 10 in. working

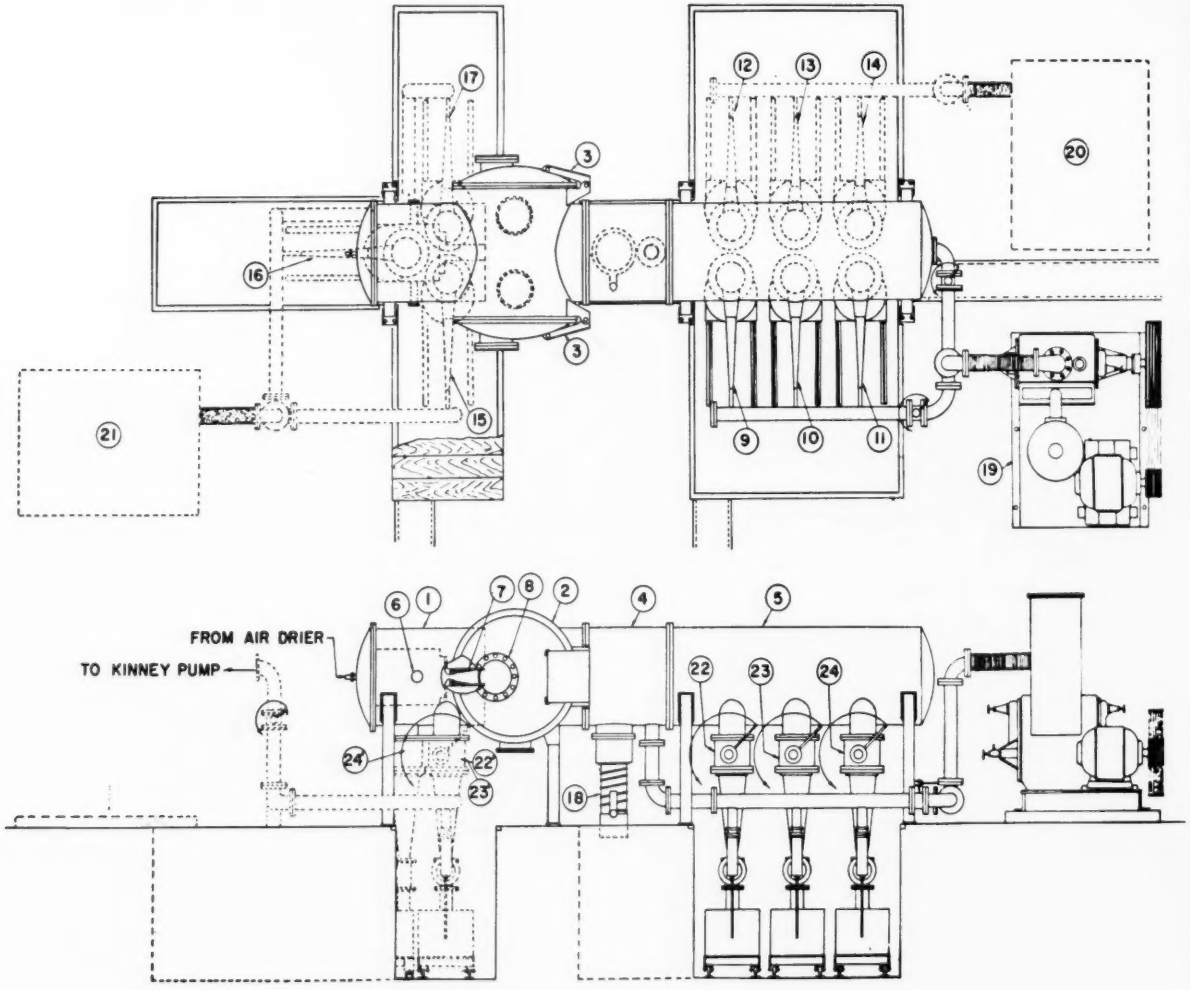


FIGURE 7. Details of the U.T.I.A. low density wind tunnel.

1, Inlet tank. 2, Open jet test chamber. 3, Hinged test section doors. 4, Valve section. 5, Surge tank. 6, Electrodes for nitrogen after-glow flow visualisation technique. 7, Slotted wall supersonic nozzle (solid nozzles to be used during initial period of operation). 8, Viewing port. 9 - 17, Edwards Co. Model 18-B-3 booster type oil diffusion pumps. 18, Edwards Model 903-B diffusion pump for evacuating tunnel to a high vacuum for leak hunting and pressure gauge calibration. 19 - 21, Kinney Model DVD 141418 backing pumps. 22 - 24, CVC-QSV-10, 10 in. quarter swing high vacuum valves.

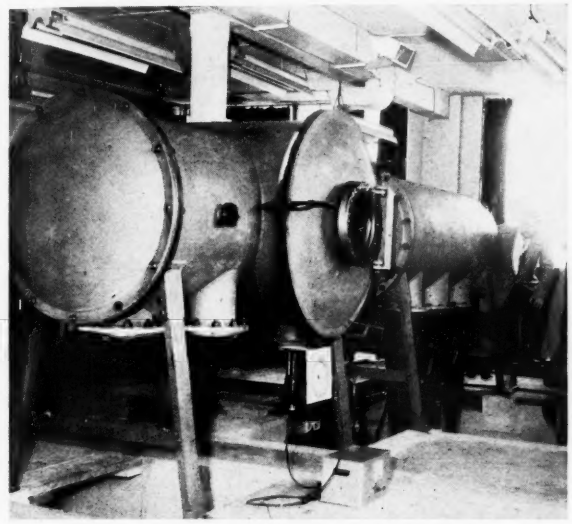


FIGURE 6. The U.T.I.A. low density wind tunnel.

section. A second, 30 in. by 16 in. high-speed tunnel was added in September 1952, and in December a transonic section was developed in this tunnel. Both tunnels are of the intermittent type and operate from a common vacuum consisting of two steel spheres with a total capacity of 56,000 cu. ft. (Fig. 8). With this capacity, running times of 15 seconds and 70 seconds are obtained with the larger and smaller tunnels, respectively, and three to five runs per hour can be made. The tunnels connect to the atmosphere through a common drier containing 34,000 lb. of silica gel. The drier can be regenerated over-night, using hot air (300°F.), the automatically controlled cycle taking 16 hours. The 10 in. tunnel (Fig. 9) is of the open jet type, chosen for flexibility of model mounting and accessibility. The 30 in. by 16 in. tunnel covers a Mach number range from 0·5 to 2·0, including the transonic region, which permits half-models of aircraft to be tested at Reynolds numbers of about 2·0 million. A slotted liner is used for subsonic and transonic testing.

These tunnels are used for testing and research and for the development of intermittent tunnel testing techniques applicable to a larger facility. In a 15-sec. run, force data over the complete range of model incidence has been obtained in the form of a pen trace on a fast-moving chart (Fig. 10) and, simultaneously, in digital form suitable for data reduction by a computor. Suitable drives for model supports and balances had to be developed.

In discussing new aerodynamic facilities mention must be made of the aeroballistic range at the Canadian Armament Research and Development Establishment. This consists of a concrete building approximately

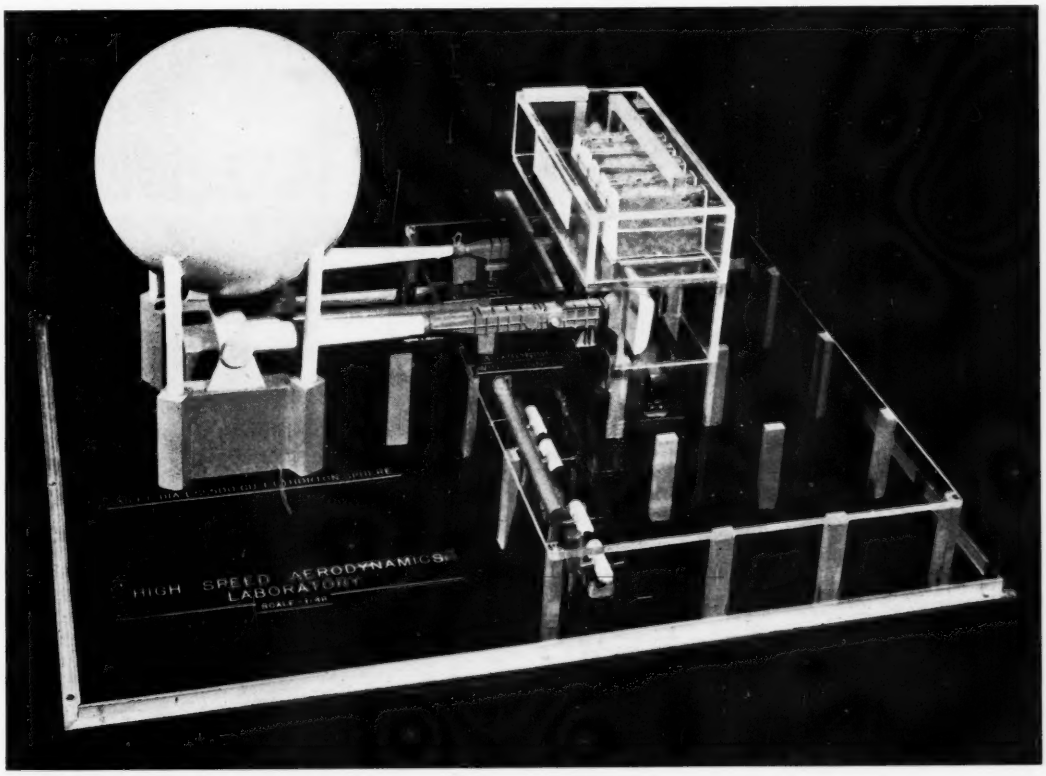


FIGURE 8. Model of the wind tunnel installation in the High Speed Aerodynamics Laboratory of the National Aeronautical Establishment.

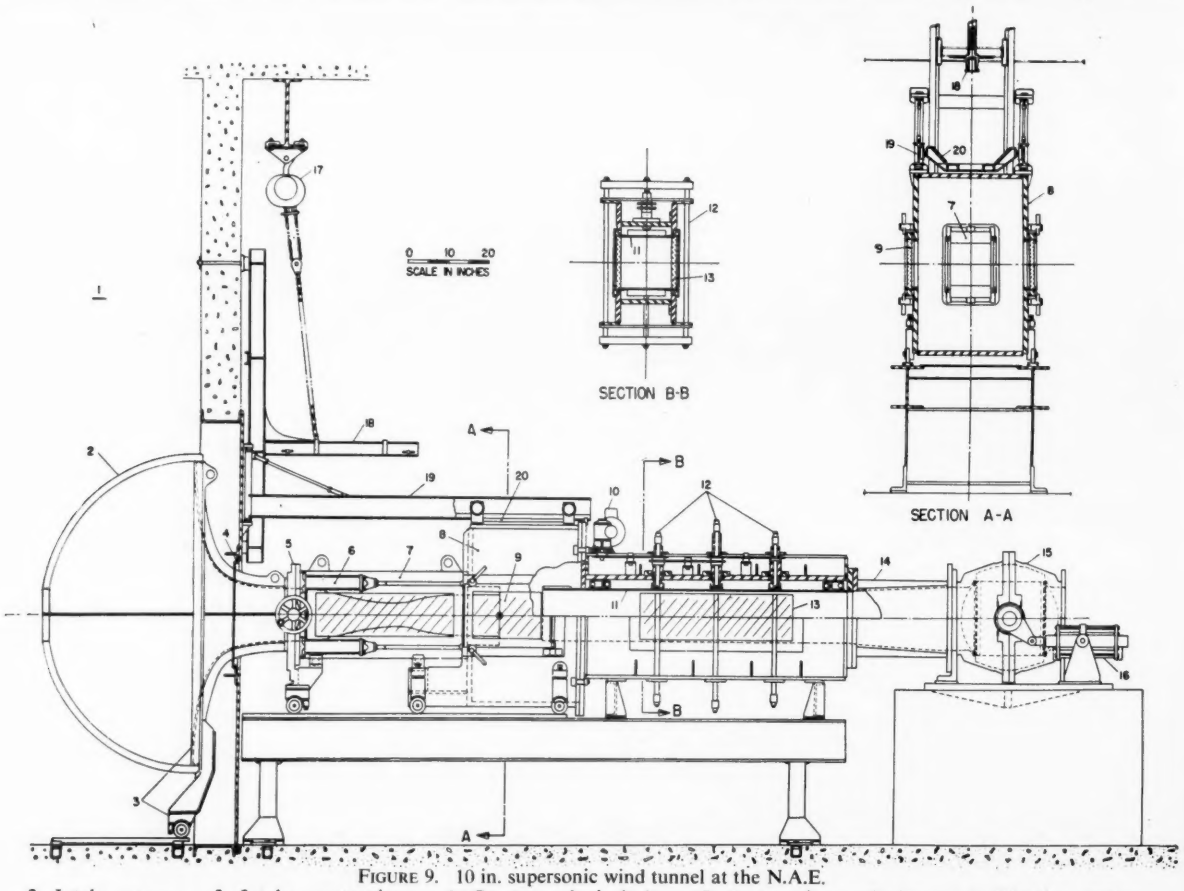


FIGURE 9. 10 in. supersonic wind tunnel at the N.A.E.
2, Intake screen. 3, Intake contraction. 6, Compressed air jacks. 7, Supersonic nozzle box. 9, Working section. 11, Variable diffuser. 15, Quick-acting valve. 17. 18, Electric lift for changing nozzle boxes.

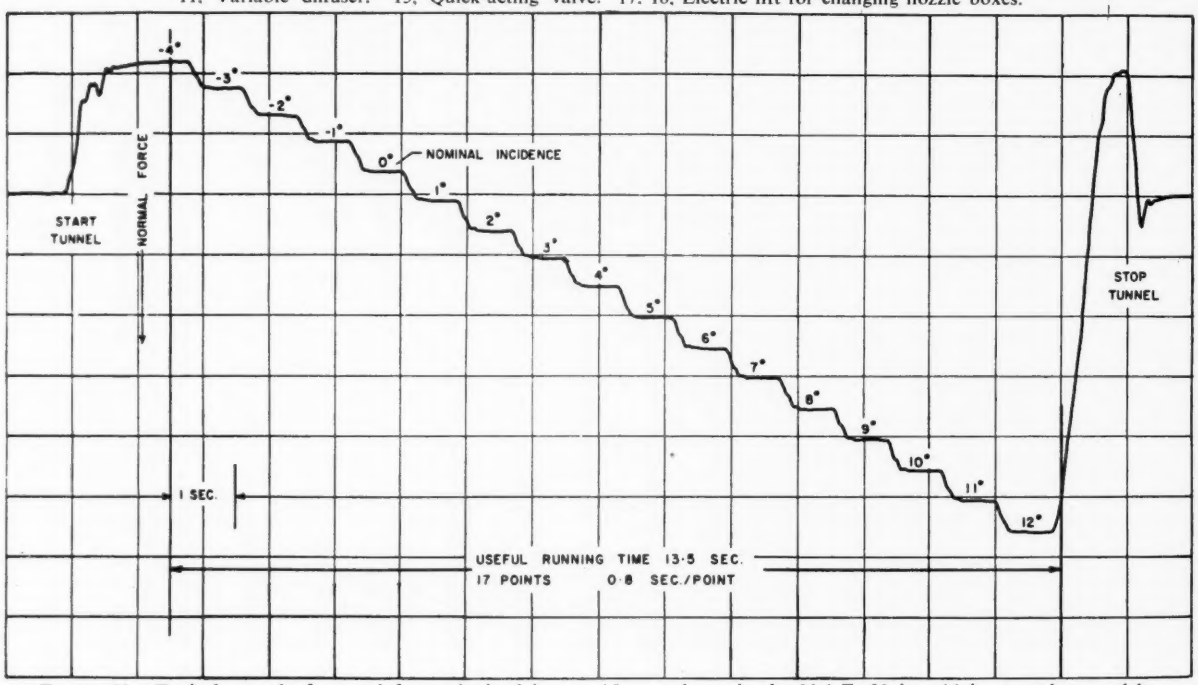


FIGURE 10. Typical record of normal force obtained in one 15 second run in the N.A.E. 30 in. × 16 in. tunnel on a delta wing, half model at $M = 1{\cdot}22$.

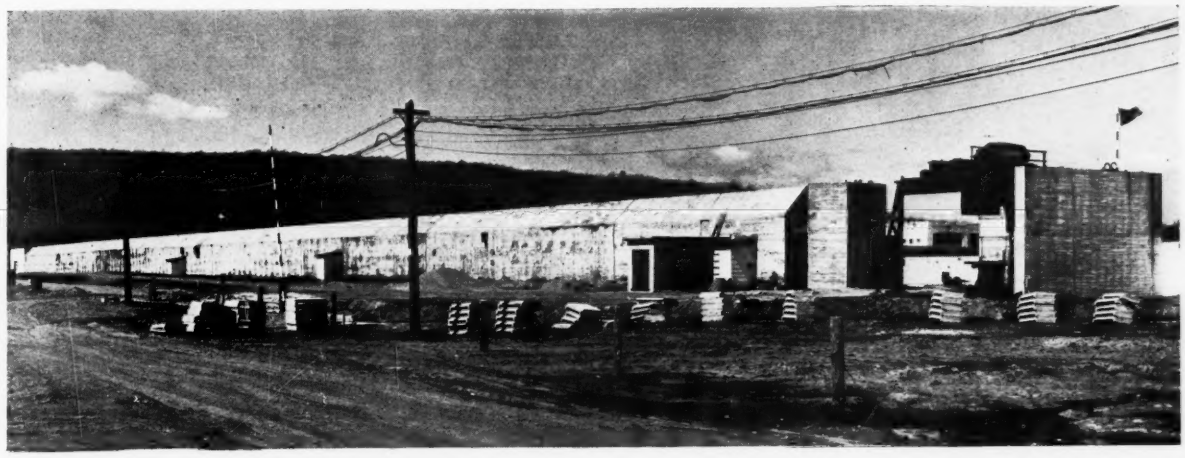


FIGURE 11 (*above*). Exterior view of the C.A.R.D.E. aero-ballistics range.

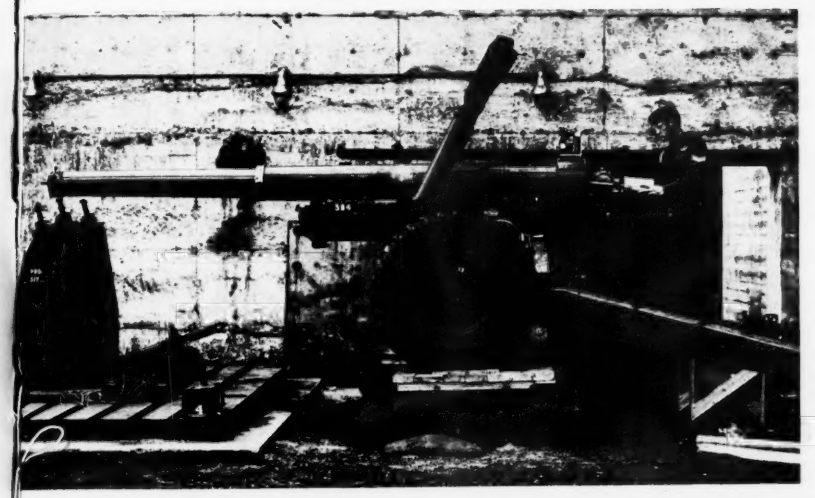


FIGURE 12 (*left*). Smooth-bored 5·9 in. calibre gun being loaded for a test.

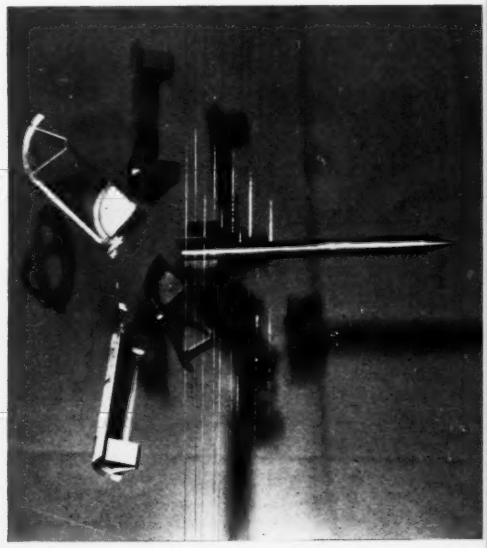


FIGURE 13 (*above*). Separation of the sabot from the model. Model speed 1,500 ft./sec. Camera operating at 5,000 frames per second. Wires are for flash triggering.

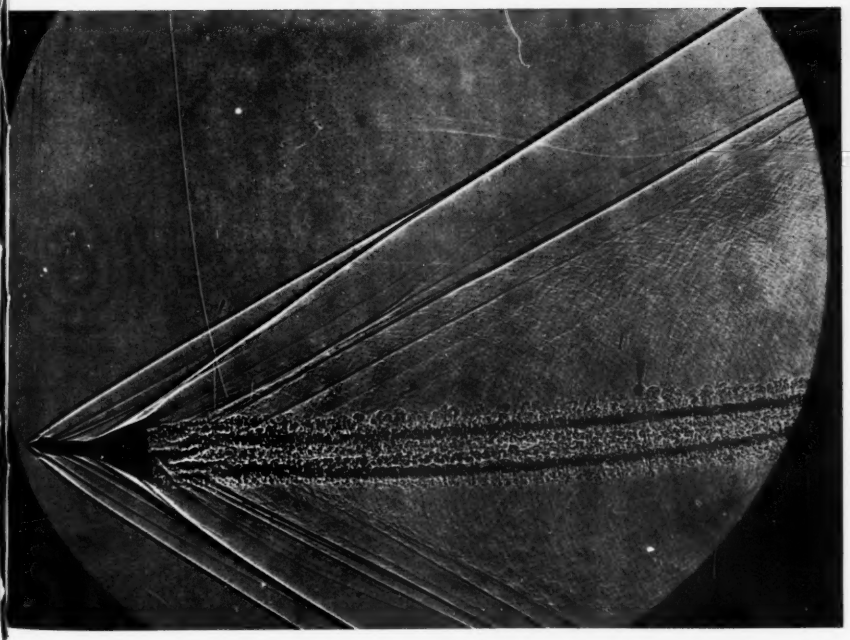


FIGURE 14 (*left*). Delta mono-wing model in flight in the range. Model is rolling, pitching and yawing at a Mach number exceeding 2·0. Note curvature of wake and trailing vortices from tip ailerons.

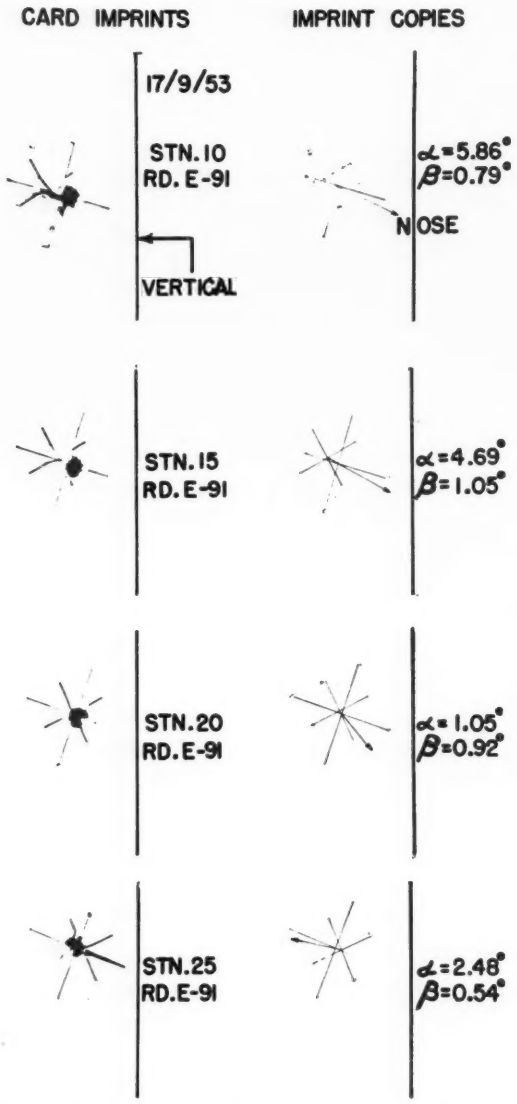


FIGURE 15. Typical yaw card imprints of model (*left*) and copies (*right*). Angles of pitch and yaw, as measured from the imprint copies are given. Muzzle velocity 2,387 ft./sec.

20 ft. square and 760 ft. long (Fig. 11). One end is closed except for an inlet hole through which the models enter. The other end of the range is open to permit the models to be trapped in a large sand butt. The models under test are launched from a smooth-bore gun (Fig. 12) by means of a discarding sabot. The sabot protects the model from blast effects or mechanical damage while in the barrel and permits the launching of odd-shaped models. The sabot is of four petal construction and these petals open and scatter rapidly from the line of fire on emerging from the barrel (Fig. 13). The sabot petals are caught by a sheet of armour plate which prevents their entry to the range. The model under test passes through a 9 in. hole in the armour plate and enters the range. Launching guns of 3·125 in. and 5·9 in. calibre have been used up to the present time, enabling the testing of fairly large scale models. Velocities up to 4,000 ft./sec. have been employed. Inside the range the velocity of the models is determined every 50 ft. by light screens. A spark shadowgraph-schlieren system employing 36 in. diameter mirrors is used for photographing the model and the air flow around it (Fig. 14). Yaw cards are employed to give the angular orientation of the model and its displacement from the line of fire as well as its roll orientation (Fig. 15).

GAS DYNAMICS

In 1949 the Board of Governors of McGill University authorised the construction of a Gas Dynamics Laboratory, within the Department of Mechanical Engineering, and appointed Professor D. L. Mordell as its Director. The objectives were fourfold. First, the training of post-graduate students in mechanical engineering leading to the M.Eng. and Ph.D. degrees. Second, the training of engineers in the type of applied research and development work which is essential for creative engineering, especially in aeronautics. Third, the prosecution of development work sufficiently original to reveal interesting problems for research and, finally, the maintenance of test facilities that would be useful in an emergency.

The Laboratory, which is located at Ste. Anne de Bellevue, some 16 miles west of Montreal, has a number of main items of equipment contained in six soundproofed test cells, having a total floor area of 4,000 ft.², as follows:

1. A compressor test rig is operated, with a capacity of 2,000 b.h.p. at 9,500 r.p.m., the power being provided by direct drive from the turbine of a modified Bristol "Theseus" engine. The air measuring system can handle up to 60 lb./sec. Electronic traversing instruments and recording gear are available. (Figs. 16 and 17).
2. A turbine test stand, being used at present for the development of an experimental coal-burning turbine, will absorb up to 1,000 b.h.p.
3. Compressed air is provided from two engine-driven compressors of capacities, 4 lb./sec. at 4 atmospheres and 2 lb./sec. at 1·5 atmospheres.
4. There are two turbine-supercharger units, one being driven by a slave compressor and combustor which permits tests to be done on both compressor and turbine. The second unit has its own combustion chamber and is operated as a jet propulsion engine.
5. A general laboratory of some 1,500 ft.² floor area is used for small scale testing and is equipped with compressed air and propane. Gas analysis equipment is available.

In 1948 the National Research Council also undertook the construction of gas dynamic experimental equipment, including a compressor and exhauster plant

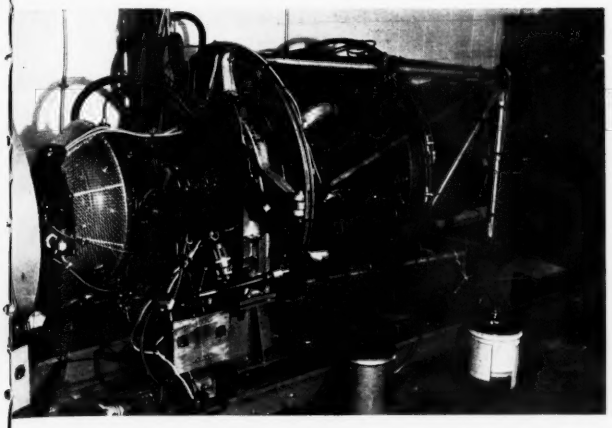


FIGURE 16. Axial compressor test rig, McGill University, Gas Dynamics Laboratory.

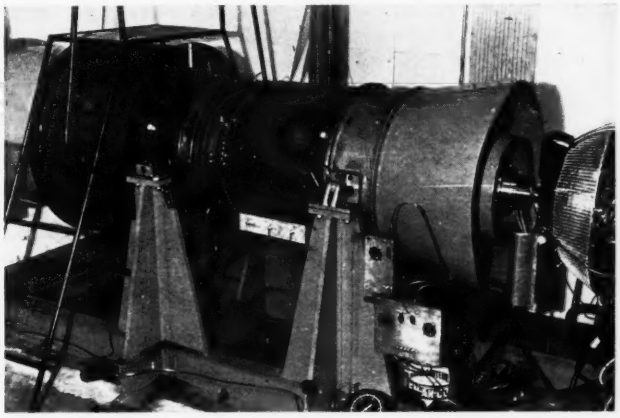


FIGURE 17. Axial compressor test rig, McGill University, Gas Dynamics Laboratory.

and various facilities for combustion research and the study of the flow of gases through the blades of compressors and turbines. While awaiting completion of the design and construction of a high-speed compressor and turbine test bed, an annular wind tunnel was provided for the study of the boundary layer flow on rotors and on isolated rotating blades at low lift coefficients (Fig. 18). The compressor or turbine blades under test are mounted on a rotor and a separately-driven fan draws air through the blades independently of their angular settings or lift coefficients.

Arising from combustion studies and a desire to learn more about atomisation of fuels and the behaviour of fuel droplets in an air stream, the second item of equipment to be provided was a suction tunnel (Fig. 19) which is capable of supporting single drops of liquid for indefinite periods.

The N.R.C. programme of turbine, compressor and combustion research will be based on the two unit compressor and exhauster plant, which was completed in 1953, and three units of test equipment. The 6,000 h.p. multi-stage two-cylinder centrifugal compressor delivers 31·4 lb. of air per second (410 cu. ft. at inflow) at a pressure of 7 atmospheres, or 53 lb./sec. at a pressure ratio of 2·25. The 2,800 h.p. centrifugal exhauster with an intake pressure between 0·05 and 0·25 atmospheres will deliver 800 cu. ft. of air per second at atmospheric discharge pressure.

The test equipment consists of a 2,000-h.p., three-stage suction turbine, a single-stage compressor test bed

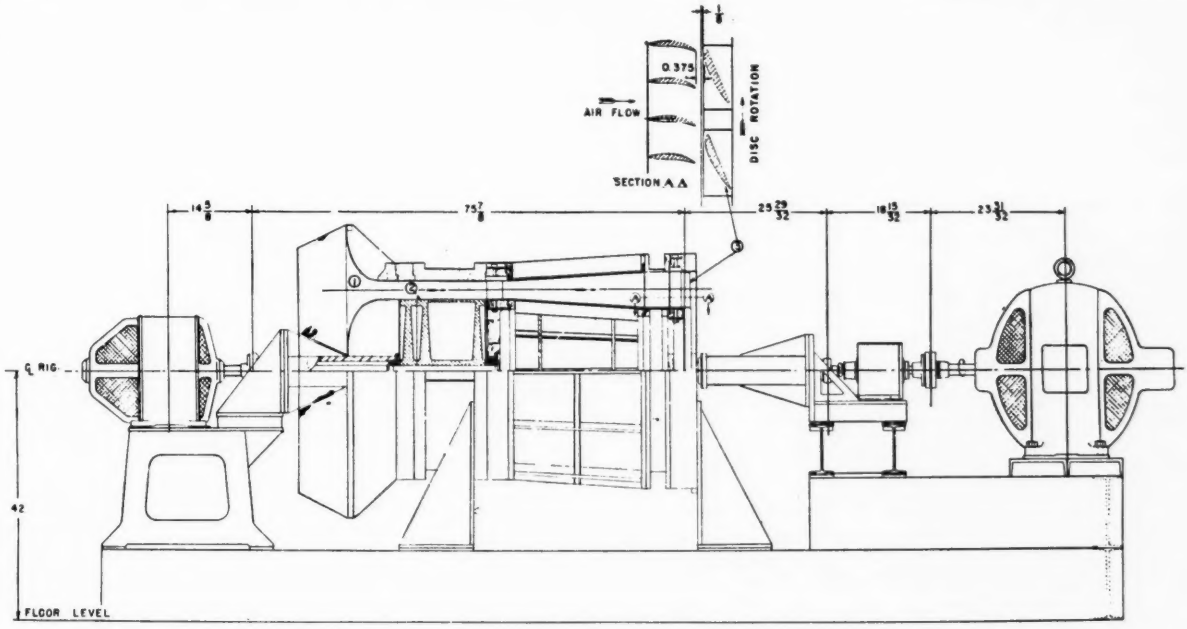


FIGURE 18. Annular wind tunnel for boundary layer and wake investigations on rotors and isolated rotating blades, N.A.E. Gas Dynamics Laboratory.

with a pressurised circuit and a 1,000-h.p. single-stage pressure turbine with hydraulic brake for power absorption.

An after-burner test rig with an annular combustion chamber for pre-heating, a water-cooled restrictor to simulate the turbine pressure drop, a reheat pipe for after-burner tests and a nozzle were assembled last year. Additional rigs for high altitude combustion studies and the investigation of heat transfer at high rates have also been provided.

Structures

At the end of the 1939-45 War our aircraft industry embarked on design and development projects, such as the A. V. Roe CF-100 all-weather fighter, the CF-102 Jetliner and the Canadair North Star. Concurrently, the N.R.C. agreed to provide static test facilities to assist industry in these ventures and to permit the Government Departments concerned to satisfy themselves that strength requirements were met. The hydraulic testing equipment[9] installed by the N.R.C. permitted wings of approximately 120 ft. span to be accommodated. Four reinforced concrete beams of inverted T-section were installed flush with the reinforced concrete floor. Two of these, on 15 ft. centres, are 100 ft. long. The other two, also on 15 ft. centres, are 85 ft. long and were provided to permit tests on swept-back wings. "Meccano" type vertical structural steel frames are erected, where desired, to provide a superstructure, the whole being stabilised by brackets, lacing bars and cross-bracing turnbuckles. Each frame is designed to carry a vertical load of 60,000 lb. The main loads are applied by "Lancaster" aircraft hydraulic undercarriage retraction jacks having a capacity of 23,000 lb. in tension and a stroke of 24 inches. Longer stroke or greater capacity can be obtained by coupling jacks together in series or parallel. Loads are applied to the specimen through sponge rubber adhesive tension patches bonded to the surface. The jacks are coupled to hydraulic consoles equipped with 12 in. Bourdon dial gauges and a portable electric pump and reservoir. The deflection of the structure under test is measured by deflection boards on which small weights are suspended by music wires running over pulleys and thence to the various points of the structure at which the deflection is required, supplemented by dial gauges at the wing root constraints. Resistance wire strain gauges with multi-channel recorders are used to measure the strain at any desired points of the structure. This equipment, although designed for static testing, has also been adapted for repeated load tests.

In addition to this equipment, the structures laboratory of the N.R.C. was provided with a 600,000 lb. universal testing machine capable of accommodating specimens 19 feet long in tension and 22 feet long in compression. It can also accommodate large specimens in bending. This machine is hydraulically-operated with a separate weighing system accurate to one-half of one per cent.

The laboratory has also developed a great deal of specialised equipment for the measurement of dynamic strains, pressures, vibrations and accelerations. Other facilities acquired in the post-war years include a German optical bench for photoelastic studies and two Schenck fatigue machines.

Much of this new equipment is more appropriate for development tests than for research. Nevertheless, the staff of this laboratory have been very ingenious in the design and manufacture of specific equipment or models for basic research in the fields of aeroelasticity and fatigue.

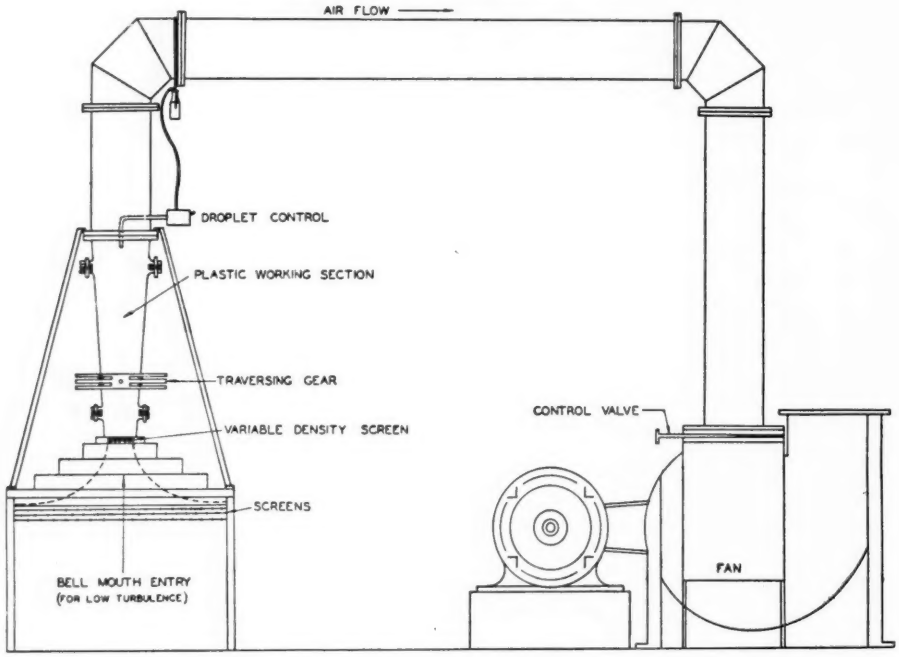


FIGURE 19. Suction tunnel for studying the behaviour of floating droplets, N.A.E. Gas Dynamics Laboratory.

Flight Research

Throughout the war years the N.R.C. aeronautical staff came more and more to appreciate the important part that flight test and research facilities can play as an adjunct to the aeronautical laboratory. Indeed, it was obvious that in many instances they would be not an adjunct but the primary facility for investigating a problem. The great importance of having a flight research establishment under the direct control of the scientists was recognised and in 1946 the R.C.A.F. agreed to participate in such a scheme to provide flight research facilities for the N.R.C. A joint N.R.C.-R.C.A.F. unit was set up on an aerodrome of its own at Arnprior, some 40 miles distant from Ottawa. This was sufficiently far removed from the headquarters of both the R.C.A.F. and the N.R.C. that the scientists and Air Force personnel living together on their own station were able to work out a *modus operandi* which has proved to be remarkably durable.

The Flight Research Section began with a mere handful of engineers and technicians teamed up with approximately the same number of R.C.A.F. officers and other ranks. The R.C.A.F. provided the aircraft and assumed the responsibility for flying and maintaining them. Two hangars were available, one being used for the installation of equipment in aircraft and the other as a flight operations hangar. The number and types of aircraft on strength varied with the work in hand. By 1949 some twelve aircraft were employed (Mustangs, Ansons, Harvards, Norseman and Expeditor). The civilian and R.C.A.F. staff together developed a considerable number of specialised instruments and equipment for their work.

In July 1953, in order to provide better aerodrome facilities, the Flight Research Section was transferred to Uplands Airport, Ottawa. Here, a new hangar with a floor area 160 ft. by 220 ft., with an adjoining office and laboratory and the necessary workshops and stores, had been provided.

A word should be said here about the R.C.A.F. Central Experimental and Proving Establishment—Canada's "Boscombe Down." Located at Rockcliffe, near Ottawa, it had grown from a small Test Flight in the early 1930's and reached maturity during the war. It was renamed after the war and, while its role has been predominantly one of testing and assessment, it has contributed materially to development. It has worked closely with the N.R.C. Flight Research Establishment. Staffed with "top-drawer" test pilots and well-qualified engineering officers, it has effectively applied a scientific approach to the many practical problems which it has been called upon to handle.

Climatic

Because a very large part of Canada lies within the Arctic and sub-Arctic and because the climate subjects almost the entire country to rigorous winter conditions for several months of the year, we have always been concerned with the influence of low temperature on men and equipment. The approach and recession of winter also introduce special operating problems which must be allowed for. Apart from our own preoccupation with these matters, the U.K. Ministry of Supply and Aircraft Industry have looked to Canada for advice and assistance in dealing with the problems of winter operations. This has led to a pleasant and stimulating co-operation extending over a good many years.

For the most part, these climatic problems have been investigated through the medium of field tests, but it has always been recognised that this has introduced its own difficulties, not the least of which has been the question of controlling the conditions. Immediately after the war the N.R.C. provided extensive cold testing facilities[10] in the Low Temperature Laboratory of the Division of Mechanical Engineering. While it is, of course, still necessary to do a great deal of work "in the field," a vast number of problems can now be tackled under much better conditions in the laboratory.

The refrigeration plant, one of the largest of its kind in Canada, is a three-stage direct expansion ammonia system, having a capacity of 250 tons and a total driving power of 1,000 h.p. Three cold chambers are available. The largest is 15 ft. square and 51 ft. long and the two smaller chambers are 10 ft. long and 10 ft. wide, with a height of 8 ft. Each of these chambers can be lowered to −80°F. In addition to normal air circulation in the chambers by blowers, auxiliary fans can produce wind velocities up to 50 m.p.h. to give any desired "windchill" factor. Internal combustion engines of 160 h.p. can be run continuously down to −80°F, provision being made for exhaust gas removal and fresh air entry.

To assist in the development of aircraft de-icing equipment, two icing wind tunnels[11] have been provided in the Low Temperature Laboratory. The 4½-foot tunnel is of the closed return type with refrigeration coils at the low velocity section. The 1,000 h.p. motor gives a 200 m.p.h. air speed in the working section, which is 11 ft. long (Fig. 20). The icing cloud is provided by a water spray at the entrance of the contraction section. The second tunnel is a blower tunnel to provide a higher speed air stream for basic research and tests of small components. It takes air from the downstream side of the refrigerating coils of the main tunnel and returns it to the upstream side (Fig. 21). With its 50 h.p. centrifugal fan a velocity of 500 m.p.h. is produced in the 5 in. by 8 in. working section.

Early in the war the U.K. Ministry of Aircraft Production provided Canada with a Bristol Blenheim aircraft for flight de-icing test and development. This was later replaced first by a Lockheed Hudson and later, by a Consolidated RY-3. All of these aircraft had drawbacks of one kind and another for the exacting requirements of this work, and eventually in 1949 the R.C.A.F. made available a Canadair North Star which was suitably modified for the work and was specially equipped with additional sources of electrical power and a number of unique instruments and items of equipment. This powerful, long-range aircraft has proved eminently satisfactory for the de-icing work and

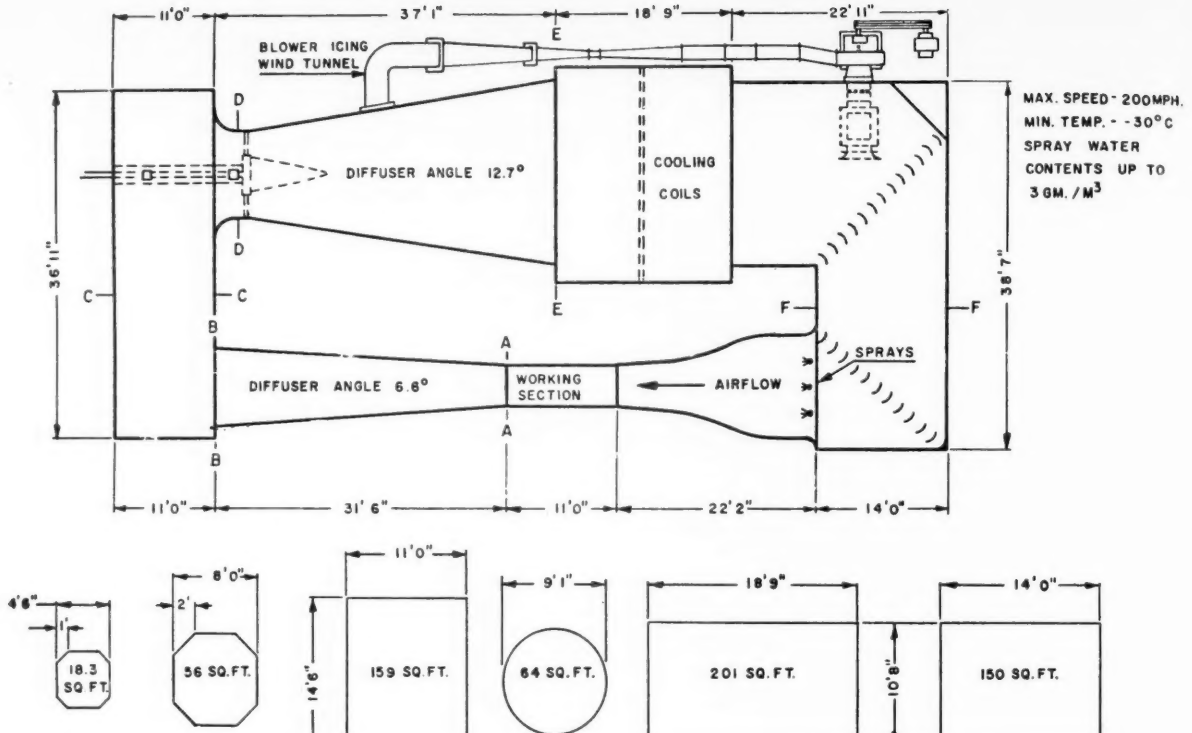


FIGURE 20. Outline of the N.R.C. icing wind tunnels.

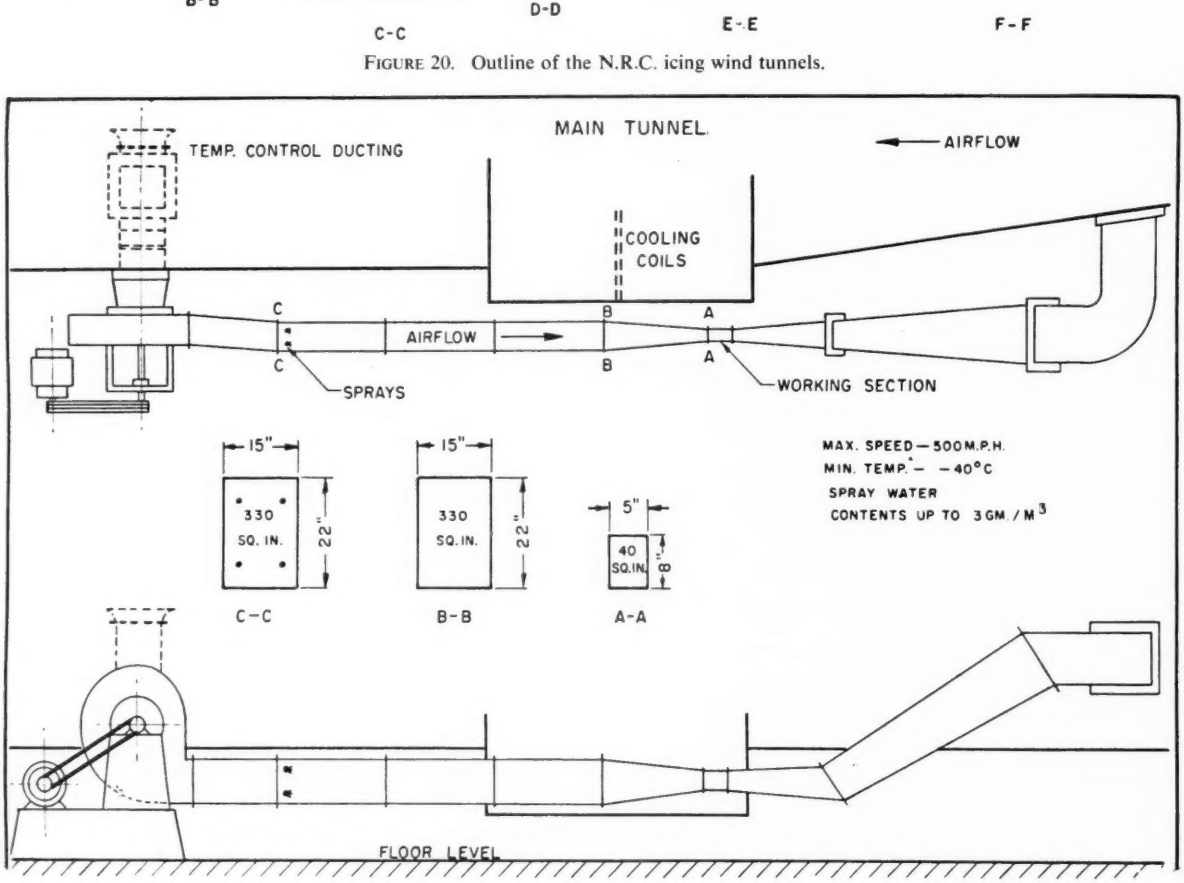


FIGURE 21. The blower icing wind tunnel of the N.R.C.

has converted what was once a very hazardous undertaking into a matter of routine operation.

Towards the end of the war the R.C.A.F. created a Winter Experimental Establishment which has been concerned mainly with field tests of aircraft and auxiliary equipment under Arctic conditions. Although not concerned specifically with research matters, this Establishment, which is located at Edmonton, has accumulated a wealth of knowledge regarding the solution of operational problems caused by low temperature and has promulgated a great deal of information concerning the design of aircraft, and their ancillary systems, for satisfactory winter operation.

Physiological

When World War II broke out almost nothing had been done in Canada in the field of aviation medicine, yet it was known from the accomplishments of the U.K. and the U.S.A. that the whole subject was of the greatest importance. At that time there was no medical branch of the R.C.A.F., the medical officers for the Air Force being supplied by the R.C.A.M.C. Due to Major A. A. James of the R.C.A.M.C. and Sir Frederick Banting, the study of aviation medicine was begun in Canada and shortly thereafter the R.C.A.F. Medical Branch was created. With support and leadership from the N.R.C. and the universities, the medical officers of the R.C.A.F. and the doctors and physiologists in the universities made great progress. Canadian contributions were predominantly in the subjects of oxygen supply systems, decompression sickness, protection against centrifugal force, motion sickness, cockpit lighting, night vision and protective clothing.

At the end of the war the R.C.A.F. created an Institute of Aviation Medicine (I.A.M.) in Toronto to centralise and to continue the excellent work initiated during the war. With the coming of the Defence Research Medical Laboratory (D.R.M.L.) at a later date the two establishments have worked closely together. The D.R.M.L. has focused its attentions mainly on research matters, while the I.A.M. has been responsible for development, but this division of responsibility is not a hard and fast one. The physiological problems of air crew are dealt with by an Aerophysiology Group which is representative of both establishments. The Physiology Group of D.R.M.L. has a broader interest but some of its efforts are of interest to aeronautics. The Aerophysiology Group has two decompression chambers covering the range of pressures from sea level to 100,000 ft. One of these can hold twenty men, with a four-man lock, and the other chamber can hold a four-man group. In addition, there is a small parasite chamber, connected to this latter chamber, which is fitted with an explosive decompression valve, allowing its pressure to be dropped from 10,000 ft. to 65,000 ft. equivalent altitude in 50 milliseconds.

The Aerophysiology Group has inherited the human centrifuge[12] which was placed in operation in Toronto during the summer of 1941. This piece of equipment, the first of its kind on the Allied side, had enabled Dr. W. R. Franks and his colleagues to make important contributions to our knowledge of the physiological reactions of men to acceleration. For instance, it was on this centrifuge that the Allies first recorded convulsive episodes resulting from "*g*." It had also enabled Dr. Franks to develop his anti-*g* suits more easily and rapidly than would have been the case if it had not been available. Recently a television camera has been added in the gondola, with a receiver located elsewhere in the building (usually on the balcony above the centrifuge pit). This enables the investigators to study the subjects more closely during an acceleration run. Equipment for taking serial X-ray pictures of the subject during a run has also been provided.

The Physiology Group of the D.R.M.L. has a motion sickness section which is equipped with a variety of swings and turntables that can make the strongest stomach weaken. These facilities have proved most useful in studies leading to increased knowledge and understanding of the unpleasant affliction known today as motion sickness.

Research Accomplishments

I come now to the most important section of my paper, a review of the accomplishments in Canadian aeronautical research during the past ten years. It is the section which caused me the most difficulty in its preparation. It is important because the evaluation of research facilities, such as those I have briefly described, must rest on the quality of the experimental results they yield, coupled with the ability of the users to interpret these results in relation to either theory or to practice. My difficulty lay in selecting from much material in many fields a few items chosen for importance, example or interest. I preferred this course to the alternative of presenting you with a complete catalogue which would have taxed your interest and your patience. I apologise to those of my friends in Canada who have done good work which, for one reason or another, I have either been unable to refer to here, or perhaps have referred to inadequately. The examples I have chosen range from basic scientific researches to engineering studies concerned with the application of scientific knowledge to aeronautics, taken generally in that order.

Shock Wave and Supersonic Studies at the Institute of Aerophysics

The excellent fundamental work undertaken at the U.T.I.A. (University of Toronto, Institute of Aerophysics) really deserves much more space than can be devoted to it here. The earliest work was concerned with the type of supersonic flow occurring in a shock tube and with the comparison between the experimental results from the 2 in. by 7 in. shock tube and one-dimensional non-stationary inviscid flow theory[13]. As a shock wave (Fig. 22) traverses the shock tube it is followed by a contact surface behind which a rarefaction wave is propagated in the opposite direction. In the region between the shock wave and the contact surface it was found that the flow is relatively free from

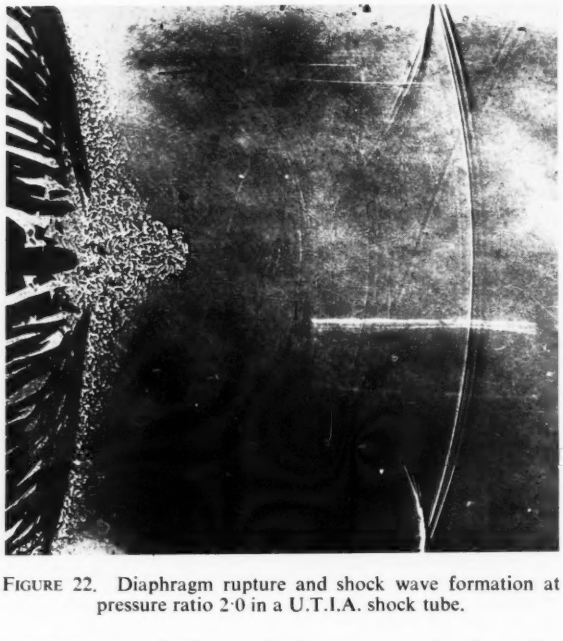


FIGURE 22. Diaphragm rupture and shock wave formation at pressure ratio 2·0 in a U.T.I.A. shock tube.

turbulence and the velocity agrees closely with theoretical estimates, even at high pressure ratios. The Mach number, however, is rather low. Behind the contact surface the flow is, in contrast, very turbulent and, although appreciable Mach numbers are obtainable, the velocity only agreed with theory up to a pressure ratio of 300 ($M=3{\cdot}4$). In this region also the duration of the flow was significantly below the theoretical value. Lobb[13] discusses the probable reasons for the divergence between theory and experiment. Lukasiewicz[6] also discusses these and other limitations of shock tubes and the possibility of extending their usefulness by intelligent design and choice of operating conditions.

Shock wave theory predicts that amplification of a shock wave is possible if it is incident on a contact surface separating two gases of appropriate internal energies. Bitondo[14] demonstrated this using air/carbon-dioxide and air/argon combinations in which there is an increase in internal energy in traversing the gaseous interface. Bitondo found that the transmitted waves in the carbon-dioxide and argon were stronger than the incident waves. A sharp gas interface was achieved with a very thin microfilm separating sheet. This film had a negligible effect in the case of weak shock waves but for the stronger shocks the wave velocity was sensitive to microfilm thickness. It was also observed in the case of the strong shocks that increasing diffusion of the gases caused deviations of the test results from the predictions of theory.

The collision of two shock waves and a shock wave and a rarefaction wave in one-dimensional flow was studied by Gould[15] in the wave interaction tube. In the case of the collision of two shock waves the observations agreed with theory (based on Rankine-Hugoniot equations) as long as the temperatures attained were not such that an appreciable amount of

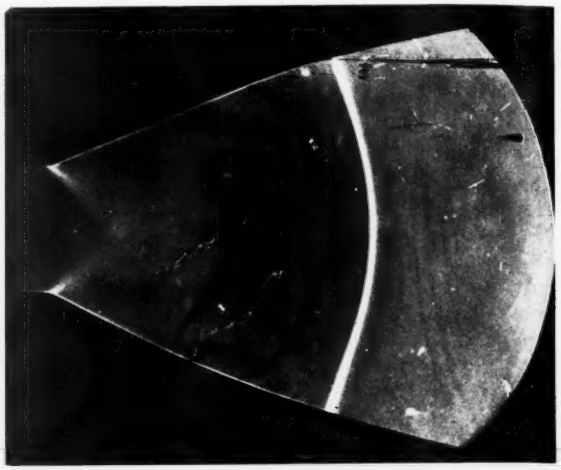


FIGURE 23. The expansion of the flow behind a plane shock wave in a Busemann nozzle, showing Prandtl-Meyer expansion, rearward facing shock, contact surface or entropy discontinuity, and forward facing main shock.

energy was absorbed by molecular vibration during the period of steady state within the tube. At higher wave strengths (and temperatures) the results could be explained more closely by the shock theory with variable specific heat. In the collision of a shock wave and a rarefaction wave the theory predicts amplification of the shock wave. This was confirmed by the experiments up to incident shock pressure ratios of 7. During the course of this work it was discovered that temperatures in excess of 4,500°K. were produced behind reflected shock waves, giving rise to luminescence in the gas.

The diffraction of a shock wave around a corner and the diffraction through a Busemann type nozzle in a shock tube of divergent cross section were studied by Parks[16]. The observed flow agreed well with that calculated from one-dimensional theory. The divergent shock tube may be a useful tool for producing supersonic flows and possibly hypersonic flows at temperatures and densities approaching those encountered in rocket and missile flight. The disadvantage which would have to be faced is the short duration of the period of supersonic flow. Fig. 23 is a schlieren picture showing the development of the flow.

Ford and Glass[17] have used the wave interaction tube to confirm the predicted wave configurations when a shock wave is refracted at a gaseous interface. (Fig. 24 shows a schlieren x, t photograph of a shock wave impinging on an air/helium interface). They used four techniques to cover all possible phenomena. Quantitative agreement with theory was good if adverse three-dimensional flow effects were not appreciable. One interesting case concerned double refraction at a gaseous layer of helium. Very strong attenuation occurred at the air/helium interface. On the return of the wave to air it was amplified at the helium/air boundary. The final pressure ratio of the wave was predicted to be less than that of the incident wave, however, because supersonic wave interactions are non-

linear. A second case of interest[18] concerned the interaction of two similarly-facing shock waves, one overtaking the other. The theory for this case[19] was experimentally verified and was found to be useful in interpreting the results of other experiments (*e.g.* the double refraction case) where the phenomenon of overtaking waves was present as an extraneous effect.

One of the earliest uses of the wave interaction tube at the Institute of Aerophysics was in the measurement of the velocity of sound in gases[20]. If the non-linear differential equations of continuity and motion for one-dimensional, unsteady, inviscid flow are solved, the speed of sound emerges as the rate of propagation of the head of a compression or rarefaction wave into the gas at rest. Since a compression wave soon leads to a shock wave, the rarefaction wave generated by bursting the diaphragm in the wave interaction tube was employed in this work. By photographing the wave on a rotating drum camera the velocity of its head could be measured, using different gases (air, argon, carbon dioxide and helium) in the tube. The results were in excellent agreement with the isentropic relation $a_0 = \sqrt{(\gamma R T_0)}$ and with experimental values obtained by acoustical methods.

The 16 in. by 16 in. tunnel has been used for a number of interesting studies. Fallis[21] has determined the heat transfer coefficient and the temperature recovery factors from transient temperature measurements at a Mach number of 2·5 in the transitional and turbulent boundary layers of a flat plate model. His results were in good agreement with earlier work at the Naval Ordnance Laboratory on cones and cylinders.

Using both the 16 in. by 16 in. and the 5 in. by 7 in. supersonic tunnels, Lee[22] conducted a series of experiments to determine the behaviour of the boundary layer upstream from a sharp compression corner. The objective was to determine the extent and shape of the region influenced by the corner and the characteristics of the boundary layer separation for laminar, transitional and turbulent flow conditions in the boundary layer.

The detached shock wave on various cones and wedges and the imbedded subsonic field were the object of study by Johnston[23]. The chordwise pressure distributions on the two-dimensional models were measured and the pressure field in the subsonic region was determined by schlieren, shadowgraph and interferometer techniques.

Still another programme conducted in the 16 in. by 16 in. tunnel involved the experimental verification of the flow conditions over a symmetrical flat plate delta wing having supersonic leading edges. For such a plan form an exact analysis[24] showed the existence of two cases in the solution of the flow over the expansion surface. Below a critical angle of attack a continuous solution did exist, while above this angle the solution was found to be discontinuous. This second case was investigated experimentally at $M = 2{\cdot}48$ and the results were substantiated within 5 per cent. of the theoretical solution found by a relaxation process.

Boundary layer measurements[25] in the 5 in. by 7 in. tunnel on a nozzle contour designed for $M = 3{\cdot}0$ in the test section, showed that the development of the turbulent boundary layer in a supersonic channel can be predicted by the approximate theory, provided that the local skin friction coefficients are computed from the wall values of density and viscosity.

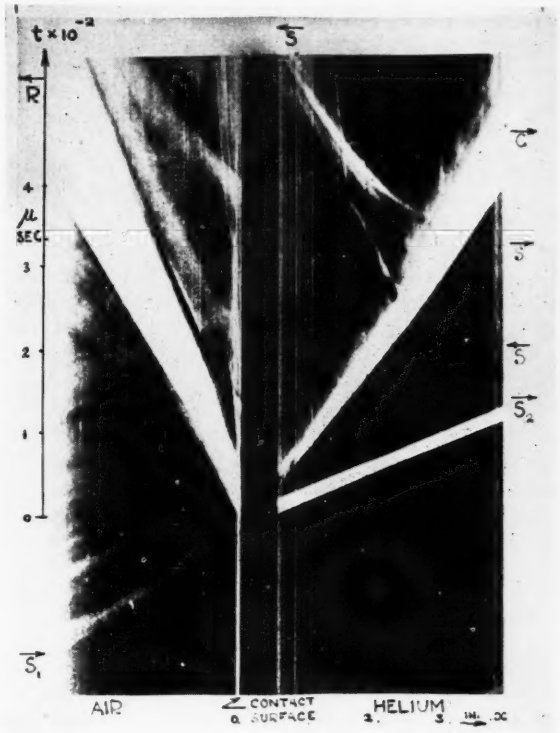


FIGURE 24. Refraction of a plane shock wave ($M = 1{\cdot}42$) at an air/helium contact surface at atmospheric pressure. x, t plane photograph.

$\overrightarrow{S_1}$ Incident shock wave $\overleftarrow{R}$ Reflected rarefaction wave
$\overrightarrow{S_2}$ Refracted shock wave $\overrightarrow{C}$ Contact front

Attempts to obtain fully developed nozzle flow at hypersonic Mach numbers in the small supersonic tunnels at U.T.I.A. have led to the realisation that flow separation from the walls of the nozzles is a universally observed phenomenon at high Mach numbers and low Reynolds numbers. Such flow separation can prevent the design Mach number from being reached[26]. This type of flow separation is now being explored.

Supersonic Tests of Low Aspect Ratio Wings

During recent years the plan form of the wings of high-speed aircraft has been the subject of spirited controversy and not a few designers have favoured the delta shape. In Canada it was felt that the National Aeronautical Establishment (the aeronautical laboratories of the National Research Council) should contribute to our knowledge of the influence of plan form and aspect ratio, through a systematic investigation of delta and other wing shapes suitable for

supersonic aircraft. This programme was begun in 1953 with tests at subsonic, transonic and supersonic speeds on two half-model delta wings in the 10 in. and 30 in. wind tunnels of the High-Speed Aerodynamics Laboratory[27]. These wings were of N.A.C.A. 0003-63 section having aspect ratios of 2·12 and 2·77 with leading edge sweepback of 60° and 53° respectively. Mach numbers in the tests ranged from 0·6 to 2·5, with Reynolds numbers, based on mean aerodynamic chord, of 1·0 to 1·6 million. In mounting the models in the tunnel variations of the reflection-plane technique were employed to assess the several effects introduced in this method of testing, including the influence of the tunnel wall boundary layer and the tare drag of the reflection plates. The characteristics of the models were measured on three-component, strain-gauge balances, the outputs of which were recorded by high-speed, self-balancing potentiometers. Reference 27 gives the results in the form of lift, drag and pitching moment variation with angle of attack and the change in the slope of the lift and moment coefficient curves with Mach number.

These preliminary tests were followed by a series of tests at Mach numbers from 1·4 to 2·5 on eleven half-wing models[28] in which the aspect ratio was varied systematically from 1·0 to 3·6. Three families of models were derived from four basic shapes, resulting in eight models of the cropped delta shape and three models with a cropped arrow plan form. Variation in aspect ratio was accomplished merely by changing the taper ratio. The models were mounted on a reflection plate in the 10 in. supersonic tunnel and the lift, drag and moment were measured, as in the earlier tests.

For all models it was found that increases in Mach number decreased the lift curve slope, the maximum lift/drag ratio, and the span efficiency factor. The minimum drag and the stability were increased.

Reduction of aspect ratio produced a small improvement, followed by a gradual deterioration, in the lift of delta wings, whereas the arrow wings showed a sustained deterioration. Reducing aspect ratio destabilised both wing types and gave substantially improved efficiency factors.

Increasing the sweepback of delta wings at a given taper ratio reduced both the lift and the minimum drag but increased the lift/drag ratio and the efficiency factor. The stability was dependent on taper ratio, however, in that at low taper ratios an increase in sweepback rendered the wing more stable, while the reverse was found at high taper ratios.

The Study of Liquid Droplets

Four separate laboratories of the Division of Mechanical Engineering, National Research Council, have had an interest in liquid droplets. The Fuels and Lubricants Laboratory is concerned with the atomisation process and the ensuing evaporation of liquid fuels. The Low Temperature Laboratory has been involved for many years, first with the characteristics of icing clouds and in particular with the droplet size and water content therein, and secondly in the provision of simulated icing clouds in the icing tunnels. The Engine Testing Laboratory has been interested in the design of spray nozzles to produce simulated clouds in icing tests of jet engines and in a simple method for measuring the size of droplets in such fogs and sprays. Finally, the Gas Dynamics Laboratory has been concerned with the evaporation and combustion of droplets and the heat transfer processes within the droplet. This wide interest has led to a number of developments and investigations of a fundamental character which have added materially to our knowledge of liquids in droplet form.

In the Fuels and Lubricants Laboratory, Sacks measured the rate of evaporation of a kerosine spray from a miniature atomiser[29] by passing a slow stream of air at a steady rate through a spray and determining by gravimetric analysis the concentration of fuel vapours in the effluent air. The rate of evaporation was found to be about 0·3 per cent. per second at room temperature. Using the results given by J. R. Joyce and his co-workers (Shell Petroleum Co.), that the Rosin-Rammler law provides the best correlation of particle size data for kerosine sprays, Sacks attempted to calculate the rate of evaporation. This was done using evaporation constants from Langmuir's equation for the evaporation of a droplet. The actual evaporation was only about 8 per cent. of the calculated amount and it was concluded that the Langmuir expression is not applicable to sprays, due to mutual interference between the droplets.

In the atomisation process Sacks believes that surface tension and viscosity play an important part and that an equation relating spray characteristics to fuel properties would have to include both of these quantities. Surface tension is not commonly measured for fuels and it was thought that a knowledge of the relationship between viscosity and surface tension would be of considerable importance. Measurements were made[30] at 25°C. for a number of fuels and it was found that there is a linear relationship between the logarithms of the surface tension γ and the kinematic viscosity ν. For petroleum fuels, with viscosities above one centistoke at 25°C., the relationship can be expressed by the formula $\gamma = 25{\cdot}1\nu^{0{\cdot}037}$.

A cloud droplet camera has been under development for several years in the aircraft and allied instrument laboratory of the N.R.C., on behalf of the Low Temperature Laboratory[31]. It depends upon the shadowgraph method of photography and requires compensation of the movement of the aircraft in order to photograph cloud droplets in flight. A high intensity, short duration, spark discharge is used as a source of illumination and rotating prisms between the objective lens of the camera and the film are employed to "stop" the droplet. In this way a true image is obtained instead of an elongated one. Two prisms are used, rotating at different speeds so that light only passes through them once during a number of revolutions, thereby eliminating the need for a conventional shutter. The speed of rotation of the prisms is adjustable to secure a stationary image on the film. The electrical circuit is so arranged that the spark discharge

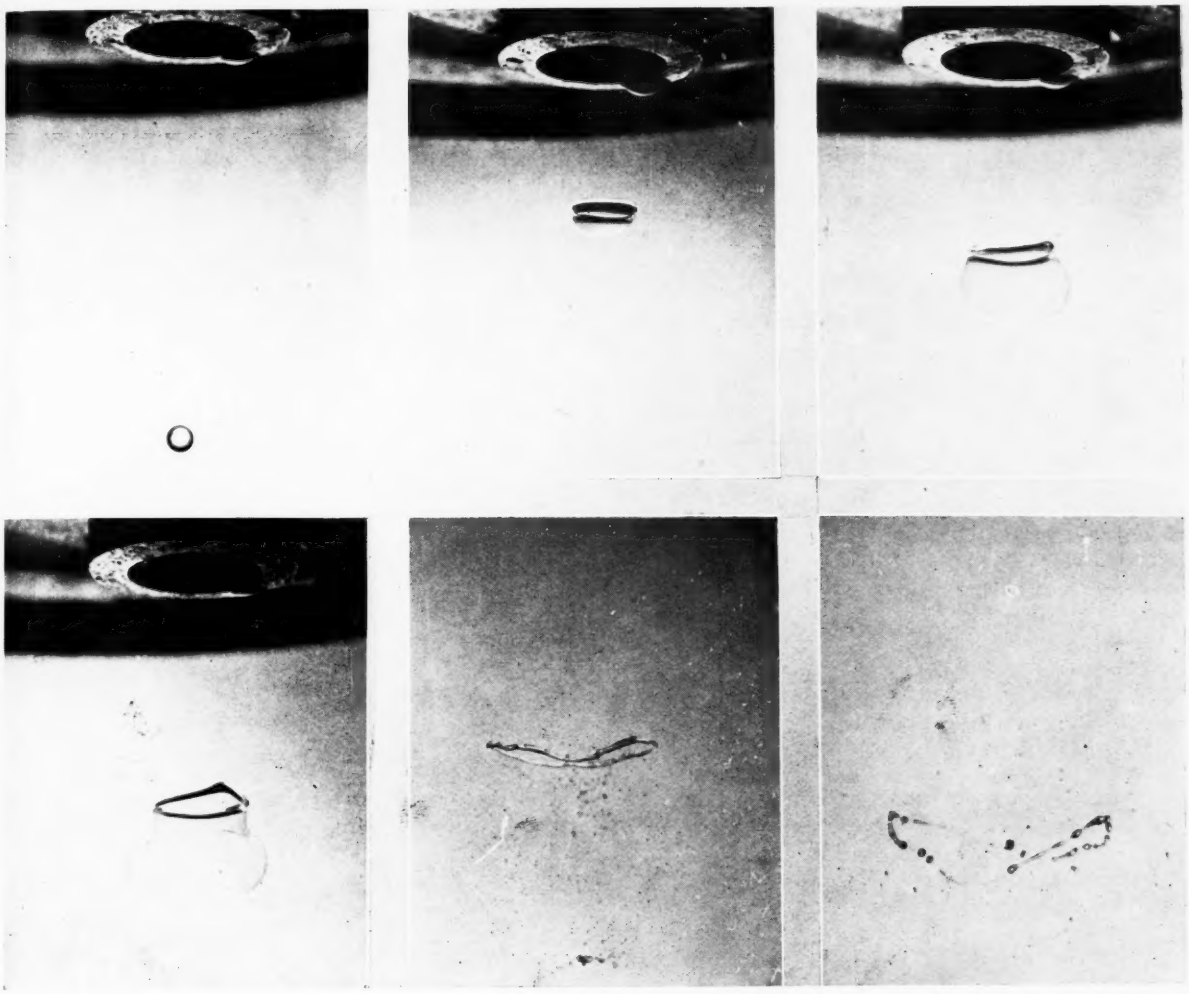


FIGURE 25. The disruption of a liquid drop in an air stream.

occurs only at coincidence of the prisms, when an exposure is possible. The camera has a magnification of 6·88 to give images of acceptable size.

The Engine Testing Laboratory has experimented[32] with swirl type and pneumatic nozzles for the "manufacture" of clouds in the laboratory. The rotary motion in the former type provides the desired atomisation. The finest spray is given by the smallest nozzle and the highest pressure, up to 1,000 lb./in.^{2} However, it was not possible, artificially, to make droplets small enough to cover fully all natural cloud conditions. The pneumatic nozzles permit compressed air to be expanded through an orifice, while water is fed through a tube to the centre of the orifice where it is atomised by the expanding air. With air pressures above the critical (about 13 lb./in.^{2}) droplet size depended primarily on the water/air ratio. The range of droplet sizes was equivalent to that found in natural clouds. This work has been extended[33] to include a study of the disruption of liquid drops and jets in an air stream (*see* Figs. 25, 26).

The method used by the Engine Laboratory for measuring droplet diameter in clouds and sprays is to collect samples on an oil-covered slide and to take a photomicrograph immediately[34]. A special oil (Shell Spirax 250) which retards the evaporation of the droplets is necessary. With ordinary lubricating, or animal or vegetable, oils the droplets would evaporate in a few seconds. There are a number of possibilities of error with this technique, including over- or under-exposure of the slides, too high or too low a speed of impact and evaporation of the droplets. Despite these the method is simple and reasonably free from the human factor. It is necessary to determine the median droplet diameter and this necessitates measuring at least 300 of them per slide, a process which can be facilitated to some extent with a specially prepared scale on which circles of varying diameters are drawn, corresponding to droplet sizes ranging from 5 microns up to 200. Comparison between the oiled slide technique and the cloud droplet camera method showed remarkably close agreement, particularly as regards

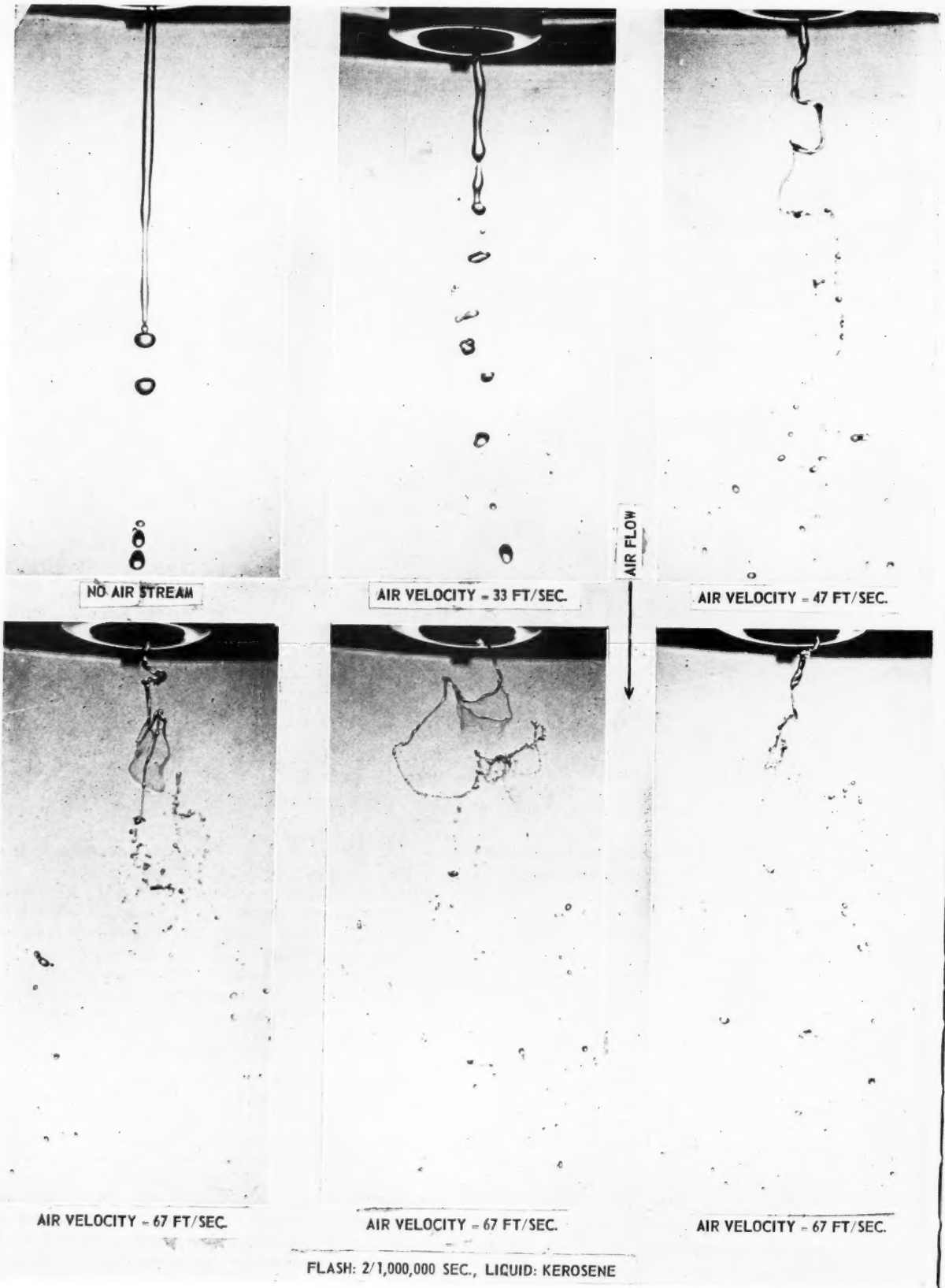

NO AIR STREAM
AIR VELOCITY = 33 FT/SEC.
AIR VELOCITY = 47 FT/SEC.
AIR FLOW
AIR VELOCITY = 67 FT/SEC.
AIR VELOCITY = 67 FT/SEC.
AIR VELOCITY = 67 FT/SEC.
FLASH: 2/1,000,000 SEC., LIQUID: KEROSENE

FIGURE 26. The disruption of a liquid jet in an air stream.

average droplet diameter. Fig. 27 shows a typical spray sample on the oiled slide.

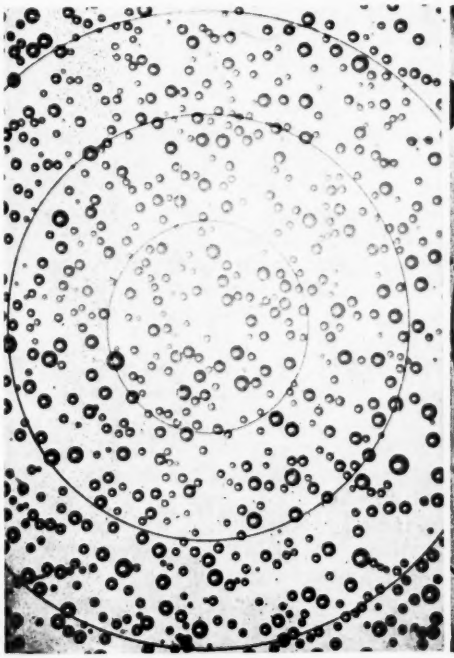
The Gas Dynamics Laboratory staff became interested in the motion of liquid drops in a gas stream and in particular the distortion and internal circulation. It was recognised that circulation must play a very important part in evaporation because of its influence on heat transfer into the droplet. This effect of circulation arises first from the transport of heat from the droplet surface to the interior and secondly, from the reduction in the thickness of the boundary layer on the droplet consequent upon the motion of the surface. The internal circulation in large water drops falling in castor oil was studied, using suspended aluminium particles in the drop, suitably illuminated and photographed.[35] For large drops the circulation appeared to agree closely with the theoretical solution given by Hadamard. With smaller drops, the vortex ring appeared to be closer to the front of the drop and no longer symmetrical about the horizontal equator. A stagnant cap then appeared to have formed at the top of the droplet, which became relatively larger as the droplets become smaller, until eventually it enveloped the whole drop and circulation ceased. Savic, who did this work, has put forward a modified theory to explain the transition from circulating to non-circulating drops but this theory, while representing the vortex motion in the drop reasonably well, gave critical droplet diameters somewhat larger than the observed values. Fig. 28 shows typical streamlines of the circulation.

There are a number of instances where the impact of liquid droplets with cold and hot surfaces is of importance. Aircraft icing and rain erosion are two examples. Savic and Boult have investigated the flow associated with such impacts[36] in connection with the mechanism of turbine blade cooling by an impinging liquid. They developed an approximate theoretical treatment which defines the shape of the spreading drop and indicates the pressure distribution over the impact plane. Experiments using a high-speed spark camera have given results in fair agreement with theory.

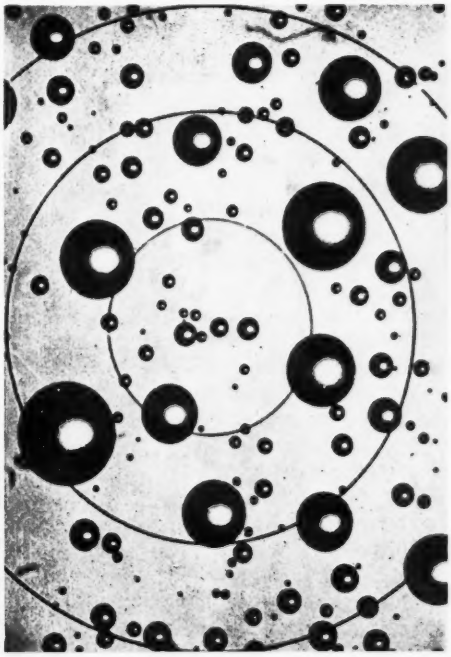
Fundamental Work on Combustion at the University of Toronto

R. O. King, for the past eight years, has been conducting a number of experiments on an A.S.T.M.-C.F.R. engine to provide information to confirm the nuclear theory of ignition, first propounded by H. L. Callendar. During this time some 24 papers have been published in the "Canadian Journal of Research," under the general title, "The Oxidation, Ignition, and Detonation of Fuel Vapors and Gases."

The first four papers dealt with earlier work done by King at the University of Cambridge in which he developed a flow method reaction chamber that enabled fuels to be completely oxidised, without explosion, at temperatures and in time periods comparable with those for an internal combustion engine. From experiments in this chamber King deduced that the oxidation of Pentane is a heterogeneous surface reaction, the velocity of which is dependent on flow configuration. He concluded further that the anti-knock effect of metallic dopes is a surface catalytic one,



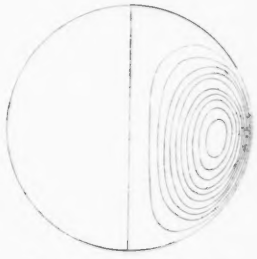
Median diam. = 30μ.
Flow number = 0·019. Pressure = 1,000 p.s.i.



Median diam. = 184μ.
Flow number = 0·537. Pressure = 200 p.s.i.

FIGURE 27. Spray samples from swirl type nozzles.

Observed Flow



Theoretical stream lines

FIGURE 28. Theoretical and actual stream lines in a circulating droplet.

dependent on the oxidation of the hydrocarbon fuel being a heterogeneous reaction. King then advanced the nuclear theory of self-ignition in which finely divided carbon particles were substituted for the nuclear drops of Callendar's theory. These carbon particles were believed to come from the lubricating oil or fuel by pyrolysis. The nuclear theory would then be applicable to such fuels as hydrogen, in addition to hydrocarbons, when burnt in a conventional internal combustion engine.

As early as 1948 King showed that hydrogen could be used as fuel for a C.F.R. engine at compression ratios up to the limit then of 10:1 and at mixtures varying from very weak to very rich, provided that the combustion chamber was kept clear of fluffy carbon. Pre-ignition and knock returned when carbon dust was admitted with the fuel.

To explain the anti-knock properties of rich fuel/air mixtures, King suggested that enrichment, in addition to its own cooling effect, accelerates the surface oxidation of the fuel, at the end-gas temperature, to carbon dioxide and steam which lower the flammability. He demonstrated, however, that in highly supercharged engines there is a possibility that even at lean mixtures the concentration of fuel is such that pyrolysis is increased, particularly at the high operating temperatures. This can result in a greater rate of formation of pro-knock finely divided carbon with a reversal of the anti-knock effect of enrichment.

From his experiments King concluded that metallic anti-knocks act by promoting high temperature surface heterogeneous oxidation of the fuel to steam and carbon dioxide and not by inhibiting a homogeneous oxidation reaction by breaking reaction chains, as generally supposed.

When King ran his C.F.R. engine on town gas (rich in hydrogen) at a 12:1 compression ratio he got severe pre-ignition if hydrogen sulphide was present. He concluded that even hydrogen could be used in the engine at the same, or higher, compression ratios if the rapid oxidation of the hydrogen to steam on the hot surfaces is not inhibited by the hydrogen sulphide poison and if nuclei of ignition are not provided by pyrolysis of the lubricating oil.

Fuels such as benzine would give knocking, if impregnated with finely divided carbon and nuclear ignition of n.-pentane could be obtained under conditions promoting the formation of carbon particles. Fuels such as acetaldehyde and diethyl ether could be used in compression ignition conditions when ignition was not caused by hot surfaces in the combustion chamber. Auto-ignition, King surmised, was dependent on the heat of oxidation reactions on material particles formed by cracking of the fuel. The timing of auto-ignition could be varied by adjusting the compression ratio to the optimum value (maximum power). King observed that the endothermic process of cracking, which is necessary for the production of nuclei required for auto-ignition, has an adverse effect on thermal efficiency.

In a letter to "Nature," Vol. 174, p. 975, 20th November 1954, King records that by taking the precaution of excluding lubricating oil from the combustion chamber as much as possible and by cooling the spark plug core and exhaust valve, he and his colleagues had run the C.F.R. engine on hydrogen-air mixtures at 1,800 r.p.m. and 12 : 1 compression ratio. The presence of finely divided carbon nuclei would have given rise to the pre-ignition which all other experimenters had encountered with the hydrogen engine.

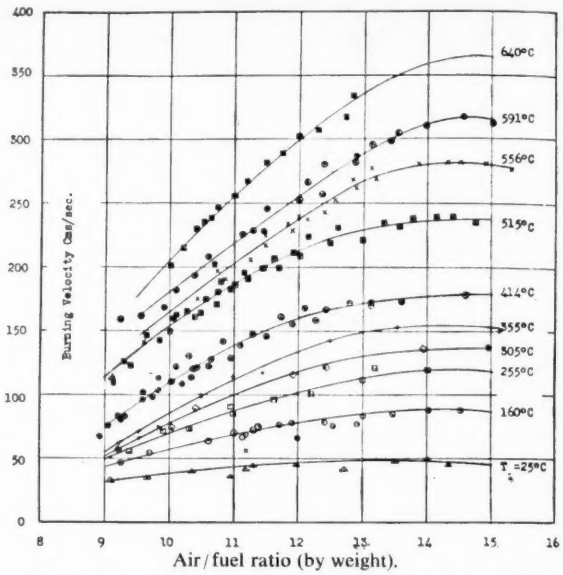


FIGURE 29. Burning velocity as a function of the initial temperature of gases.

Gas Dynamic Research at McGill University.

Early in 1951 preliminary experiments were made by G. G. Daw at the Gas Dynamics Laboratory, McGill University, on an after-burner in which the fuel was injected ahead of the turbine blades, after the manner proposed by Dr. H. Schmitt. Such a system has a number of advantages including the reduction of losses in the diffuser and flameholder, a shorter length of after-burner unit and a cooling of the turbine blades. The system makes use of the ignition delay following injection, which varies between 1 and 10 milli-seconds. The temperature rise then occurs downstream from the turbine which, in this case, acts as the flameholder. The work at McGill on a modified General Electric turbo-supercharger, and with relatively primitive equipment, demonstrated that such a system was practicable, that it permitted steady after-burning, with spontaneous ignition and with a realisation of expected performance.

McArthur and Srinivasan attempted a determination of the influence of change of working fluid properties on the performance of turbines and compressors. By injecting water into the inlet gas stream the values of C_p and γ, the specific heat at constant pressure and the ratio of the specific heats, could be varied over a small range. The results of the turbine rig tests were

unsatisfactory, mainly due to inadequate instrumentation, but they did suggest that there was a deterioration in turbine performance (adiabatic efficiency) with an increase in C_p and a decrease in γ. In the case of the compressor rig tests the adverse effect of water injection was much more conclusively demonstrated[37] by a reduction in pressure ratio, efficiency and mass flow with reduction of γ.

A general study of the mixing of cold air jets with a hot gas stream was initiated by J. P. Beauregard. Since the pressure losses in gas turbine combustion chambers are partially due to mixing losses, an attack on this problem was deemed desirable. The cold air jet was introduced at right angles to the hot gas stream and experimental results were derived for the influence of orifice diameter, temperature and velocity ratios on the rate of mixing and the limit of penetration. Further work is now in hand to improve the generality of the results.

The effect of the initial temperature of reacting gases on the velocity of flame propagation appears to have been studied only at relatively low temperatures. Srinivasan[38] and Bula[39] at McGill have investigated flame propagation at elevated temperatures using a vertical insulated burner supplied with propane and air, the latter being preheated in a gas to air counterflow heat exchanger. A propane-fired combustion chamber supplied hot gases to the gas side of this exchanger. The temperature of the air passing up the burner tube was controlled, then, by the propane flow into the combustion chamber. Fine control was obtained by adjustment of a secondary air flow to the combustion chamber. The temperature of the air going to the burner could be held to within $\pm 5°C.$ in the range 0-700°C. The burning velocity determination was made from the total area of the visible inner cone of the flame. This was photographed at 1/500 sec. and the films were projected on to a screen at 8 : 1 magnification. The outline of the inner cone was traced therefrom and the surface area was determined by geometry. The results of the measurements at the low temperatures (below 300°C.) were in reasonably good agreement with similar work done by others (*e.g.* Dugger at N.A.C.A.) which might be taken as substantiating the validity of the results at higher temperatures. The burning velocity showed a sevenfold increase (Fig. 29) in going from room temperature to 640°C. The observed variation of flame speed with temperature could be predicted either by the thermal theory of Semenov or the diffusion theory of Tanford and Pease within the limits of experimental error, but above 550°C. the thermal theory appeared to be more precise.

Bula, using the same equipment, investigated the effect of varying the oxygen concentration on flame propagation at elevated temperatures. He used three concentrations by weight, 0·2045, 0·2320 and 0·2750 at preheat temperatures ranging from 20°C. to 640°C. Increasing the oxygen concentration increased both the burning velocity and the flame temperature appreciably. The experimental results were compared with the predictions from the thermal and diffusion theories. Below about 330°C. the diffusion theory seems the more reliable, but above this temperature neither theory gives close agreement with the experimental results. The work is now being extended to temperatures of about 900°C.

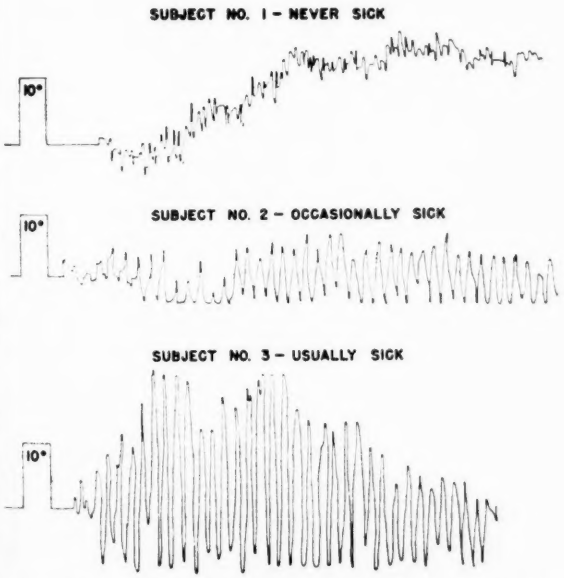


FIGURE 30. Recordings of the head movements independent of the swing of three different subjects swung through a 70° arc with a frequency of 16 cycles per minute. The swing was hand-propelled.

Work in the Aero-medical Field

Because it is still a disqualifying factor in the selection of air crew trainees and because it has a high incidence in airborne and amphibious operations, motion sickness remains an important problem within the three Armed Services. For some years it has been known that the non-auditory membranous labyrinth in the head is an essential sense organ for motion sickness. It was also known that acute vertigo and nausea can result when the head is subjected to angular velocities in planes at right angles to each other, which could induce an effect, similar to precession, on the labyrinthine mechanism.

In 1950, Johnson, at the Defence Research Medical Laboratories and his colleagues at the Institute of Aviation Medicine, began recording the motions of the heads of R.C.A.F. Flight Cadets during tests on a hand-propelled swing. They discovered[40] first that there was considerable difference among the various subjects as regards independent motion of the head and second, that there was a good correlation between the incidence of motion sickness and the extent of the independent head movement (Fig. 30). When head motion was prevented a very high proportion of subjects who had previously vomited, when the head was free to move, showed no symptoms under similar swing motions.

Later work[41] with a large-scale field trial, using Army personnel as subjects flown in a Hadrian glider and in a Dakota aircraft, confirmed these early results.

These trials showed conclusively that restriction of head movement will result in a consistent decrease in the symptoms of motion sickness under all turbulence conditions.

With the new decompression facilities, investigations have been pursued in the field of high-altitude physiology, directed towards pressure breathing and blood circulatory reactions to simulated altitude. For preventing anoxia above 45,000 ft. a combination of pressure helmet, pressure vest and anti-*g* suit was investigated. Breathing pressures of about 80 mm. mercury would protect against anoxia up to about 60,000 ft. Experiments were accordingly done with subjects exposed to these breathing pressures, but marked respiratory and cardio-vascular changes took place and it was found that subjects could tolerate such a combination only for an average of about five minutes. The difficulty lay in the fact that this combination did not afford complete counter-pressurisation of the body surface and permitted loss of blood to the periphery and an effective decrease in circulating blood volume. It was suggested that greater efficiency of the combination would result if an increase of the body surface area over which effective counter-pressure is applied could be attained.

Balancing of Aircraft Controls

About fifteen years ago aircraft designers in Great Britain were plagued with excessive variation in the control heaviness of aircraft coming off the production lines[42]. The trouble was present in aircraft of all types, both large and small, and had its source in the close degree of control balance required as a result of the large size or high speed of aircraft, coupled with the desire for maintaining, or even increasing, the manoeuvrability. The Royal Aircraft Establishment was busily engaged with the problem, particularly with specific cases, and it was suggested that Canada might undertake long-range investigations in this field. It was suggested that knowledge was needed of the influence of all the various design parameters on the hinge moment and the rate of change of hinge moment with angle of attack and angle of deflection of the control surface. It was admitted at that time that one of the greatest difficulties was to get any reasonable agreement between the results of wind tunnel tests on control surface characteristics and the measured performance in flight.

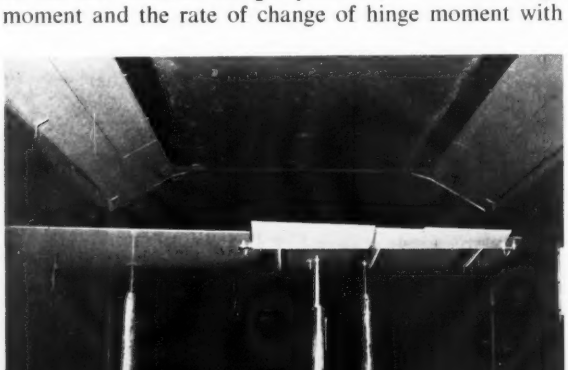


FIGURE 31. Model of Harvard aircraft outer wing in wind tunnel.

The National Research Council undertook to work on this problem in 1941 and there and then began a lengthy programme of wind tunnel and flight research aimed at elucidating some of the difficulties. The initial experiments were made with the aileron of the Harvard aircraft, the tunnel tests being done on a 4/10 scale model of the outboard wing. The work was then extended to various types of ailerons replacing the standard Harvard aileron on the aircraft and on the wing model used in the tunnel tests. During the war the main effort went into attempts to correlate wind tunnel and full-scale results and was also directed at investigating the influence of control surface design features on hinge moment. The work was continued after the war on a broader basis to include more rigorous theoretical treatment. Because of the complexity of the mathematical work, an attempt was made to use the electrical analogy tank as an aid in solving problems of two and three-dimensional potential flow about an aerofoil with a control surface. In addition, considerable effort was expended in exploring the influence of the boundary layer thickness on control balance, following the lead of Dr. Preston at the National Physical Laboratory.

At first, the agreement between wind tunnel and flight measurements of control surface performance was poor and merely confirmed the experience of both the R.A.E. and the N.A.C.A. The Canadian investigators[43] did suggest a number of reasons why the correlation was poor in their experiments, including the presence of friction in the model and full-scale measuring equipment, aileron fabric deflection in the full-scale tests, improperly assessed boundary conditions in the tunnel tests and failure to apply all the significant corrections both in the model and full-scale tests. Later work by the N.R.C.[44], involving improved techniques and better knowledge of the corrections to be applied, yielded sufficiently close agreement between the model and full scale to permit the tunnel tests to be used for quantitative design purposes. The variation was within the range that can be expected among nominally identical aircraft, despite the fact that the size of the model in comparison with the tunnel dimensions necessitated relatively large wall interference corrections (Figs. 31, 32 and 33).

Because of the failure of lifting-line theory to predict, from aerofoil section data, the hinge moment characteristics of finite span control surfaces the N.R.C. did a series of wind tunnel tests on the influence of aspect ratio on hinge moments[45]. The results, which were included in Ref. 45, all applied to low Reynolds numbers (below $1{\cdot}5 \times 10^6$) because at higher speeds certain inconsistencies were believed to be due to distortion of the model under high air loads. A subsequent investigation was therefore made[46] with a model of twice the chord to determine the influence of

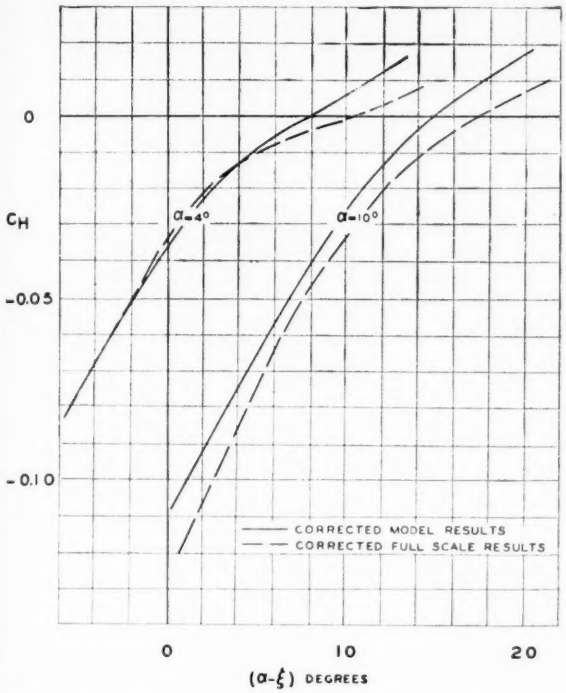


FIGURE 32. Hinge moment coefficients for flat aileron with fixed tab.

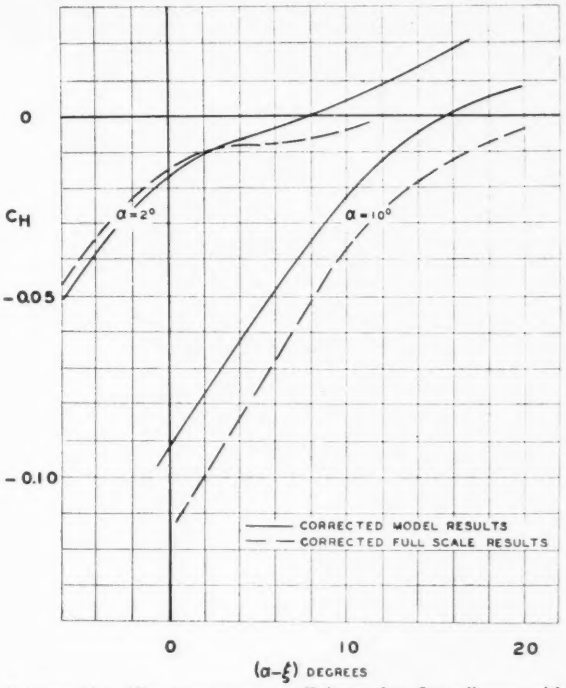


FIGURE 33. Hinge moment coefficients for flat aileron with geared tab.

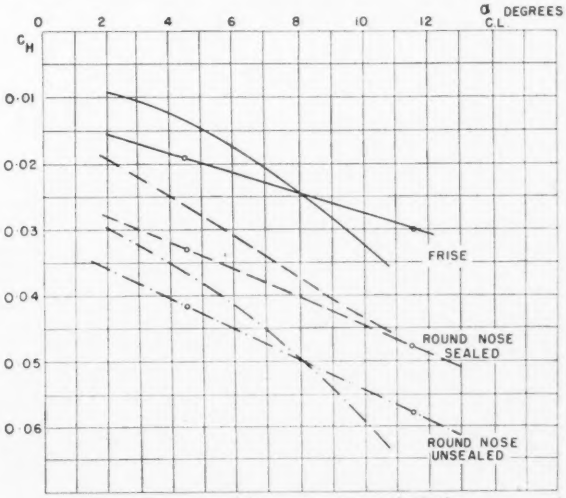
Reynolds number (up to 5×10^6). The results of this work agreed substantially with similar work done at the N.P.L., except that the N.R.C. values of the variation of lift with control deflection were about 20 per cent. in excess of the N.P.L. values.

In Ref. 42 it was suggested that control surface hinge moments for finite span controls might, with the failure of lifting-line theory, be calculated from lifting-surface theory. Such a method of calculation was developed by R. S. Swanson and S. M. Crandall of the N.A.C.A. Templin[47] of the N.R.C. compared tunnel measurements and calculated values of the lift and hinge moment parameters for balanced and unbalanced control surfaces and showed that the N.A.C.A. method of correcting for aspect ratio gives results in good agreement with tunnel measurements.

On the theoretical side Mandl[48] has performed the laborious calculation of the two-dimensional hinge moments at zero deflection for the outer wing panel of the Harvard aircraft with flat-sided Frise ailerons and round-nosed sealed and unsealed ailerons. The method consisted of determining the velocity and hence the pressure distribution around the aerofoil, making due allowance for the presence of the boundary layer (as measured in flight) and its influence in reducing the Joukowski value for the circulation. Spanwise integration of the two-dimensional hinge moments, derived from the pressure distribution, yielded the overall hinge moments of the control surfaces. These calculated values were in rough agreement with hinge moments measured experimentally in flight (Fig. 34).

The Design, Construction and Testing of a Tailless Glider

In 1942, G. T. R. Hill came to Canada as Scientific Liaison Officer representing the United Kingdom. His long interest in tailless aircraft, coupled with the knowledge that Jack Northrop was doing things on a really grand scale would have frustrated a man of lesser enthusiasm and tenacity. With his charm and



Two-dimensional hinge moment calculations.
Straight lines are calculated values.
Curved lines are experimental values.

FIGURE 34. The variation of three-dimensional hinge moment coefficient with incidence.

persuasiveness he talked the Associate Committee on Aeronautical Research and the National Research Council into the formidable task of designing, constructing and test flying a tailless glider. This effort involved the Structures Laboratory in the basic design; the Aerodynamic Laboratory furnished design data from wind tunnel model tests and investigated the spinning characteristics in the spinning tunnel (Fig. 35). The Aircraft Instrument Laboratory developed all the special instruments and recording equipment that would be needed in the flight tests and the R.C.A.F. and, later, the Flight Research Section of the N.R.C. conducted the actual flying tests (Fig. 36).

The glider had a span of 46 ft. 8 in. and a gross weight of about 3,880 lb. The centre section had a straight span of 16 ft. with outer wings tapered and swept back 39·3° (quarter chord). The centre section chord was 10 ft. 4 in. Two separate cockpits were provided, one for the pilot and one for the observer and a retractable tricycle undercarriage was fitted. The wooden structure consisted of a single laminated spar with conventional ribs and a relatively thick plywood skin. Elevons at the wing tips provided lateral and longitudinal control. The whole of the wing tips were movable through $9\frac{1}{2}°$ in order to permit longitudinal trim. End fins and rudders were fitted at the wing tips and a conventional split flap was provided.

The first flights were made by the R.C.A.F. Winter Experimental Establishment at Edmonton, initially with Squadron Leader Kronfeld, R.A.F., as the pilot, and later with R.C.A.F. pilots, using a Dakota as the towing aeroplane. Take-off speed was 90 m.p.h. I.A.S. and the speed on tow was 110 m.p.h. The technique was to tow the glider to 10,000 ft. and release it. Flight characteristics were measured during the descent which usually occupied about ten minutes. Touch-down speed at landing was 60 m.p.h.

In the initial tests, with c.g. at about 21·4 per cent. of the mean chord, the longitudinal stability was good, but since it was not possible to trim the glider with flaps up and wing tips at neutral, a more aft' position of the c.g. was considered desirable. As Northrop pointed out,

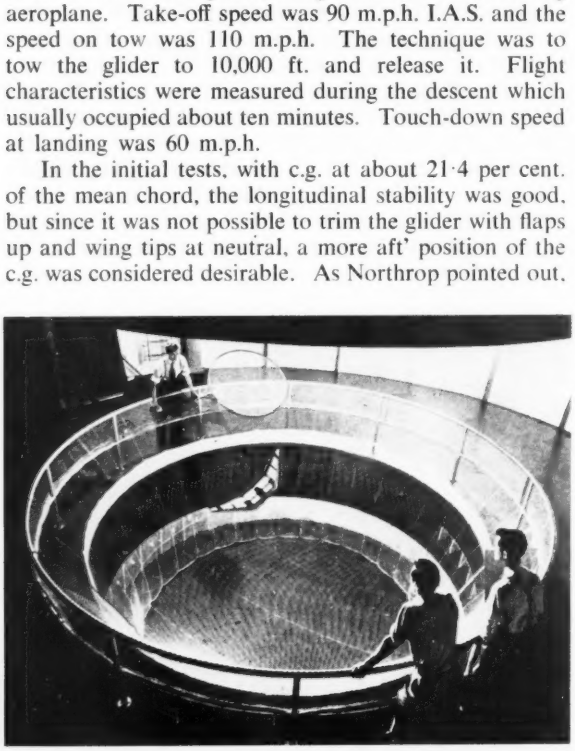


FIGURE 35. A model of the N.R.C. Tailless Glider in the spinning tunnel.

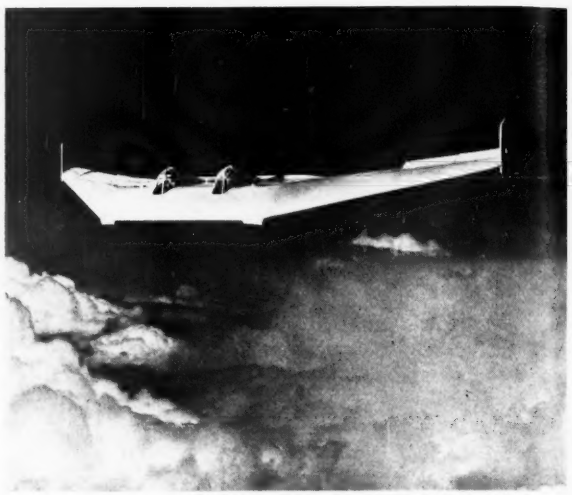


FIGURE 36. The N.R.C. Tailless Glider in flight.

however[49], in the 35th Wilbur Wright Lecture before the Society, it is the lateral stability and control factors that really differentiate all-wing aircraft from conventional ones. The Canadian tailless glider was no exception. The directional stability appeared to be marginal and a directional oscillation with poor damping was observed, both on tow and in free flight. The longitudinal and lateral control were adequate but the rudders were ineffective, with a sense reversal at indicated speeds above 110 m.p.h. It was found desirable, in turns, not to use the rudders at all. The trimming tips were useful for trimming at high lifts and for relieving the stick forces at high speeds.

The detailed measurements made during flight were published in two reports[50, 51]. The so-called rudder force reversal encountered in the early flights was found to be due to static lateral instability of the glider and small side force coupled with directional stability. The rudder power was quite inadequate at high lift. The static lateral instability was unimportant at high speed but with flaps down it prohibited coarse use of the rudder for picking up a wing. Pitching and rolling moments due to sideslip were small under all test conditions.

Rolling performance of the glider was good and could be predicted closely from wind tunnel data and lifting surface theory. Longitudinal short period oscillations were heavily damped while the phugoid was undamped with flaps up, but its period was sufficiently long that it gave no trouble in the handling of the aircraft. With flaps down the phugoid was damped. The characteristic asymmetric oscillation was undamped with flaps up but was damped with flaps down. There appeared to be a cross coupling of the asymmetric and symmetric motions evidenced by oscillations in air speed having the same periodic structure as those in sideslip and yaw.

Wind tunnel tests showed that cambered wing tip fins would give a considerable improvement in the damping in yaw obtained with symmetrical fins. Tests

also showed that the particular low drag aerofoil section used for the glider was very sensitive to protuberances on its upper surface. This explained a flow separation observed in flight and associated with the canopy shape. Modified canopies were designed with large fairings which improved the flow and reduced the drag of the glider. Both the cambered fins and the modified canopies, with fairings, were added to the glider and yielded the improvements anticipated.

The Repeating Parachute

It used to be said about a certain complex bombsight that it enabled a bomb to be dropped into a pickle barrel. It is, however, still very difficult to drop a stable streamlined object from any reasonable height and have it arrive with great precision at a pre-selected point on the ground. It is much more difficult to attain accuracy when an article is dropped by parachute because of the variations in parachute performance and, more important still, the longer time under which the falling system is under the influence of wind drift and the changes occurring therein. In most instances there is no need to be highly accurate in parachute operations, but on occasion it is desirable to be able to drop supplies or stores with good accuracy.

A few years ago the Flight Research Section of the National Aeronautical Establishment gave considerable thought to this problem and was able to derive a solution which is applicable in those cases where a very low terminal velocity is not essential. H. T. Stevinson decided that the problem might be solved by a parachute which, after opening to check the forward motion, could be collapsed during the major portion of the vertical drop and re-opened just prior to ground impact. In this manner the influence of wind drift would be minimised. He and his colleagues began experimenting with slotted parachutes in which, by suitable arrangement of the shrouds and cords, the gores were made to assume a pitched attitude, when inflated, similar to that of windmill blades. Such parachutes rotate rapidly and wind up the shroud lines, thereby causing the parachute ultimately to collapse. In the meantime the torque in the shroud lines causes the falling body to rotate slowly in the same direction, a rotation which persists after collapse of the parachute, until the shroud lines are unwound again and the parachute re-opens. In their latest designs Stevinson and his co-workers have been able to arrange for the parachute itself to reverse its direction of rotation after collapse, in order to provide a closer control on the time of re-opening.

The problem was attacked intensively, using a special test rig mounted on a light panel wagon (Fig. 37). These ground tests were supplemented by actual dropping tests and at the same time work was progressing slowly but steadily on the development of a theoretical treatment which would explain the complicated motion of the parachute and which would enable control to be exercised in the design so that any desired performance might be achieved. It was found, for instance, that variation of the design parameters could yield a parachute which would not collapse, or one that would go through one cycle only of open-collapse-reopen, or a parachute that would perform multiple cycles in succession. It was obviously desirable to develop the theory to indicate how this might be controlled in design.

The dynamical behaviour of a rotating, self-collapsing parachute[52] is controlled by so many variables that it was necessary to reduce, by simplifying assumptions, the number of them included in the equations of motion. The motion was considered in two parts, the linear motion along the trajectory and a rotary motion, with coupling between the two. The solution of the linear motion gives the velocity at any point in terms of the terminal velocity, the terminal velocity along the tangent path and the distance along the trajectory. The solution of the rotary motion was derived in the form of the amount of twist in the shroud lines, in radians, in terms of distance along the trajectory. As yet the theory is not fully developed and it is necessary to incorporate some experimentally determined parameters and relationships. In carrying out the theoretical calculations for comparison with actual drop tests it was generally necessary to divide the trajectory into five definite regions, each governed by the configuration of the parachute and its extent controlled by the rotary motion of the system. These regions are as follows:

1. The horizontal or near horizontal segment; parachute squidding, no rotation.
2. Parachute fully open, rotation just beginning.
3. Parachute and body rotating in same direction until collapse of parachute.

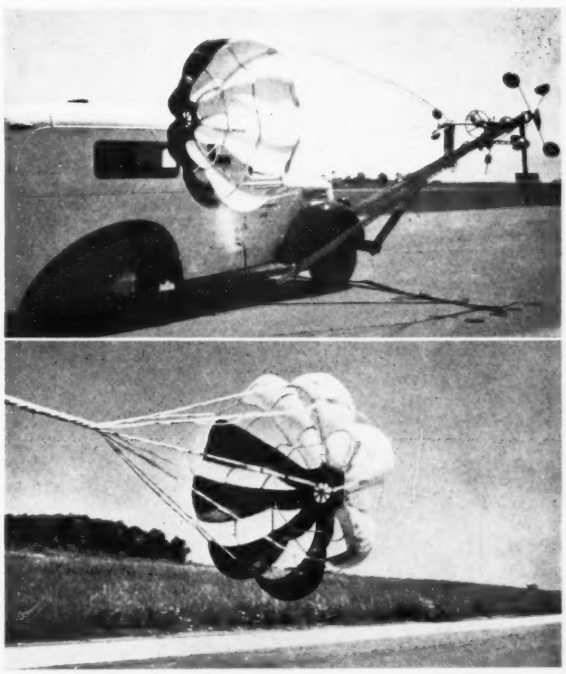


FIGURE 37. Ground test rig for repeating parachutes; and (*lower picture*) repeating parachute.

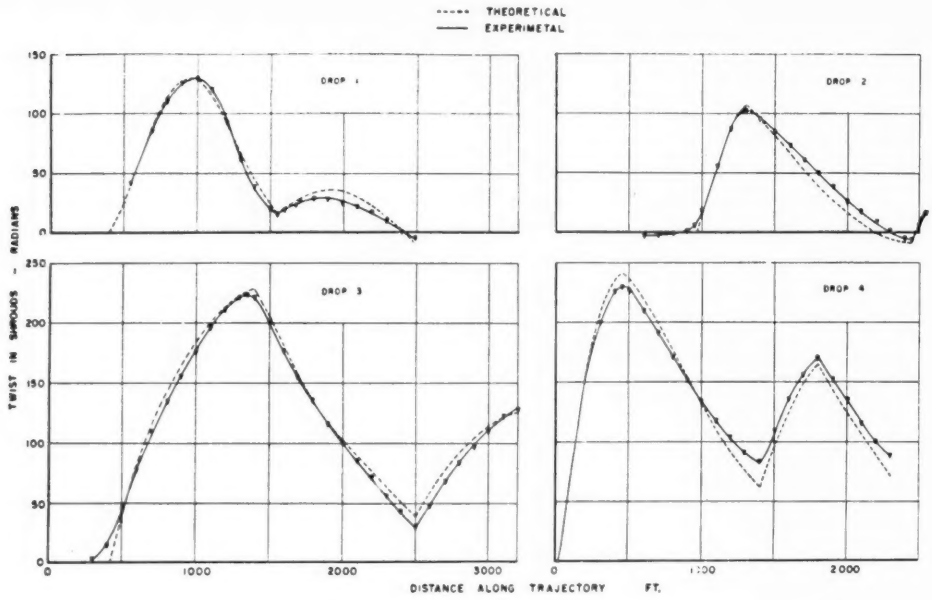


FIGURE 38. Comparison of theoretical and experimental twist in the shroud lines of repeating parachutes.

4. Parachute again squidding, rotating slowly in opposite direction until re-opening.
5. The open cycle is repeated, beginning with region 3.

A comparison of theoretical and experimental results for the twist of the shrouds is given in Fig. 38 for four cases. In the first three the parachutes were of the single cycle type and the fourth was a multiple-cycle type. The first parachute had 48 shroud lines and the other three had only 16. The agreement is, on the whole, very good.

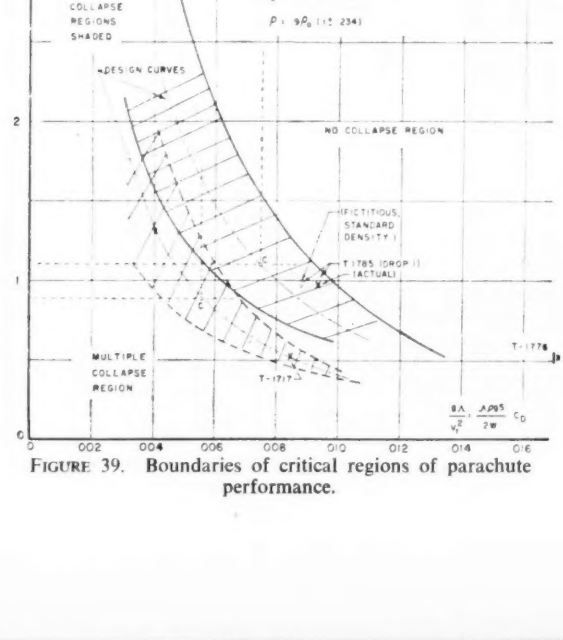


FIGURE 39. Boundaries of critical regions of parachute performance.

Mandl and Stevinson[53] next extended the theory to deal with systems scaled to any size. The objective also was to determine the parameters or combination of parameters which primarily control the boundaries that separate the regions of non-collapse, single collapse and multiple collapse. An attempt was also made to estimate the effect of air density on the cycle. To accomplish all this it was necessary to simplify the theory and, by making further assumptions, eliminate the dependence on empirical relationships. By assuming that the parachute pitch is constant, instead of a linear function of the twist in the shroud lines, it was possible to reduce the number of regions of the trajectory which must be separately considered to three—the open phase, closed phase and the re-open phase. The effects of the various parameters on the motion were then studied and graphs were drawn relating these parameters and showing the boundaries between the critical regions of parachute performance (Fig. 39).

The results of this latest work are helpful for design purposes but the authors caution that the results are approximate only, since a number of features of parachute performance, notably centrifugal force, had to be ignored.

Aeroelastic Work at the N.R.C.

In 1945, A. H. Hall, of the Structures Laboratory, N.R.C., began a limited study of wing flutter[54]. His approach was indeed a unique one in that he proposed an experimental investigation in the wind tunnel, using a rectangular wing in which the stiffness in torsion and deflection and the distortion forms in torsion and deflection could be chosen before each test. By covering as wide a range as possible for these variables he hoped to determine their influence on flexure-torsion flutter characteristics. The 20 in. by 60 in. wing was of uniform, symmetrical profile. The single dural spar was

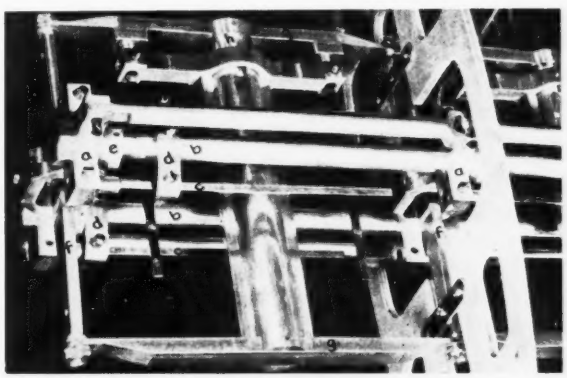
ingeniously articulated at fifteen stations (Fig. 40) with the torsion elements freely pivoted on the flexure elements so that torsion and flexure characteristics were quite independent. Each span element was independently spring-stiffened against distortion in twist and shear (normal to the plane of the wing). To eliminate the problem of stretching of the fabric cover, bending displacements were simulated by shear deformation. This was arranged by making each span element a pin-jointed parallelogram deformable normal to the plane of the wing. The active lengths of the torsion and shear stiffness springs in each span element were adjustable by means of clamps. Three general arrangements of stiffness distribution, in both flexure and torsion, were employed by a linear variation of the active spring lengths between root and tip. These arrangements corresponded to positive, zero and negative taper. Various combinations of these stiffnesses in flexure and torsion were examined.

Before conducting the wind tunnel tests the static stiffnesses and spanwise form of deformation were obtained by direct loading and the vibration frequencies and amplitudes of deformation were examined by forcing springs. The tunnel tests were done at zero angle of attack, the behaviour of the wing being recorded by photographing a number of pea lights distributed along the leading and trailing edges, using fixed mirrors to reflect the light into the camera so that corresponding images of leading and trailing edges appeared side by side on the film. By arranging the film motion to be at 45° to the line of images, each image produced a separate and continuous trace. In reducing the film records, corresponding flexural and torsional displacements were computed and superimposed so that amplitude, phase and frequency could be read directly.

It was found that for the range of distortion modes studied, a reference section at 0·75 span was the most suitable. The ratio of static to dynamic stiffness for various reference sections between mid-span and tip was found to be much less than unity and varied considerably with the chosen reference section. Dynamic stiffness values were accordingly used in all calculations. Flexural and torsional modes of oscillation were defined by a plot of the deflection and twist of each section of the span in terms of the wing tip deflection and twist. In the case of flexure, the modes for vibration and flutter were almost identical for all stiffness distributions. This was not true for torsion, where the modes at some points on the span differed by as much as 30 per cent. for some stiffness distributions. For all practical purposes the flexural flutter mode was found to be independent of the torsional mode and also of the wind speed. There was, however, an indication that the torsional flutter mode responded to changes in flexure. The critical flutter speed factor (Fig. 41) plotted against the ratio of flexural to torsional stiffness gave agreement with the theory for zero structural damping at the high values of the stiffness ratio, but was about 10 per cent. low at the smaller values of stiffness ratio. If structural damping is taken into account (Fig. 42) the experimental values of the critical flutter speed factor are about 20 per cent. to 25 per cent. below the theoretical. The flutter frequency parameter plotted against the stiffness ratio gave fair, but scattered, agreement with classical theory (Fig. 43).

In the post-war decade we have seen the emergence of structural stiffness as possibly the most important characteristic of a wing structure. This importance lies in the profound effect which stiffness has on flight performance and control and in the ever-increasing difficulty that the designer has in providing adequate stiffness in the face of a continuing demand for thinner wings. Hall, of the N.A.E., has contributed to this subject by developing a simplified theory for the determination of the deformation of swept wings[55]. In the root triangle, defined by a line (*CN* in the lower part of Fig. 44) drawn from the rear spar attachment joint perpendicular to the locus of section shear centres, there is a complex system of stresses and strains. The deformation analysis of a wing is usually concerned with the behaviour of the outboard wing but this is significantly influenced by the deflections of the root triangle, even though these are small. Hall's theory, which is concerned with deformation but which, he suggests, might be extended to a simplified stress analysis, applies to the root triangle and gives the displacements of the locus of section shear centres up to the outboard edge of the triangle. Outboard deformations are then computed, taking into account the initial inboard values.

In developing the theory the load resistant structure of the wing is assumed to be concentrated along the



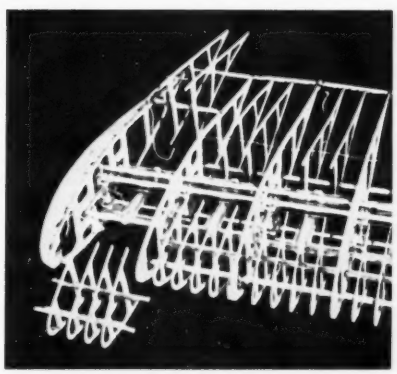


FIGURE 40. Wing construction details for flutter study.

structural reference axis $O\xi$ (Fig. 44) taken as the locus of the section shear centres. For a swept wing (lower part of Fig. 44) outboard of the root triangle the direction of the principal strains is parallel to $O\xi$, *i.e.* identical with the angle of sweep Λ. Where the wing joins the fuselage structure, however, the direction of principal strain is approximately parallel to the axis OY, which is normal to the longitudinal axis of the aircraft. If the direction of principal strain is assumed to be synonymous with the angle of sweep, then it is apparent that in proceeding inboard across the root triangle the effective angle of sweep is gradually reduced from Λ to zero. Consider now an unswept wing (upper half of Fig. 44), with the load resistant structure again concentrated along $O\xi$ the structural reference axis. Slopes and deflections at any section, due to an applied loading, may be resolved relative to the axis OX which is inclined to the structural reference line. Any desired spanwise variation in deflection and rotations, relative to the inclined direction, can therefore be reproduced by one of a great many possible distributions in load. It follows therefore that one can determine a complementary loading distribution (involving shear, bending and twisting) along ON, a portion of the structural reference axis, such that the deflection and rotations at N will be identical with those for the swept wing case. This fictitious load distribution is approximated by a simple polynomial with constant coefficients, the values of which are determined by the principle of least work. In determining this loading distribution it is necessary to satisfy the two boundary conditions that the direction of principal strain must be parallel to OY at the root and $O\xi$ at the outboard edge (N) of the root triangle. The loading at the outboard edge must also correspond to the loading at that section resulting from the loads on the outboard wing.

Hall made an experimental check of this simplified theory by constructing a number of plastic wing models with various degrees of sweepback and subjecting them to various loadings. The measured deflections, which were reported at the Third Anglo-American Conference at Brighton in 1951*, agreed extraordinarily closely with the theoretically predicted values.

The Loads on Aircraft Skis

Aircraft have been operated on skis during the winter months in Canada for a good many years. In recent times, however, winter operations at the major aerodromes and airports have been conducted by aircraft with conventional wheel undercarriages. Nevertheless, there are still many small communities in Canada where winter flying operations entail the use of ski-equipped aircraft.

In the design and development of aircraft skis there has been a great ignorance regarding the nature and magnitude of the loads imposed on the skis during take-off and landing and during taxying and manhandling of the aircraft while it is on the ground. Ski manufacturers relied to a great extent on past experience and such requirements as did exist were often in doubt and were subject to quite arbitrary changes from time to time. One of the most frequent locations of failure was the nose of the ski, yet for its design manufacturers employed their own arbitrary conditions of loading. It was realised that an improved basis for ski-plane design was urgently needed and that this would require a knowledge of the loads on the skis, the undercarriage and the aircraft itself. The N.R.C. agreed to extend its work on skis to a determination of the loads imposed on them during operations. It had long been known that these loads are to a great extent dependent on the type of snow encountered and the N.R.C. tests were accordingly to be extended over more than one season and were to be conducted at widely separated locations to provide a variation of snow conditions. The results of the tests were to be made available for the revision of I.C.A.O. requirements, where necessary, as a Canadian contribution to the airworthiness code of that body.

It was decided that the vertical loads should be measured on a statistical basis. This would permit a comparison with similar loads for aircraft on wheels and would also enable a quantitative evaluation to be made of the spring pedestals often used to replace the resilience of tyres. The drag loads were to be measured

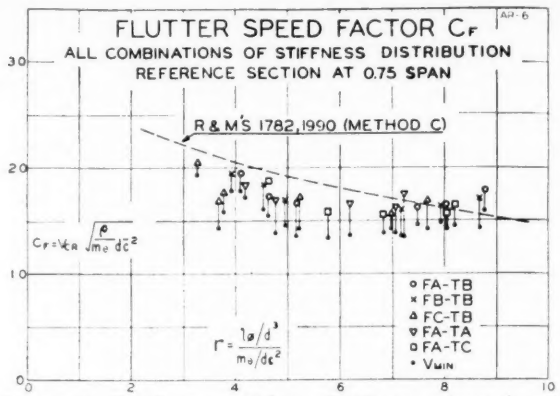


FIGURE 41. The flutter speed factor C_F (theory and experiment).

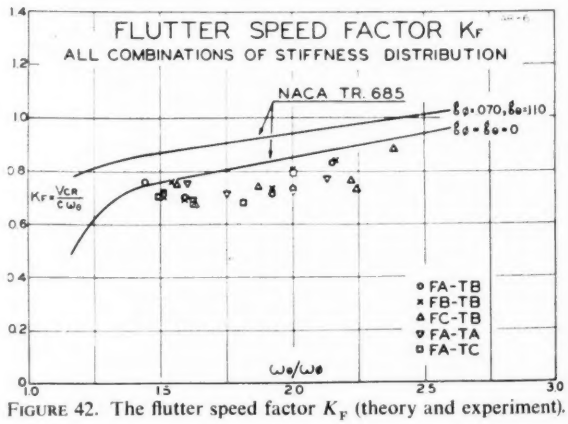


FIGURE 42. The flutter speed factor K_F (theory and experiment).

*An Experimental Study of the Static Stiffness and Deformation of Swept Wings with Uniform Chord. A. H. HALL. Third Anglo-American Conference, *Royal Aeronautical Society*, 1951.

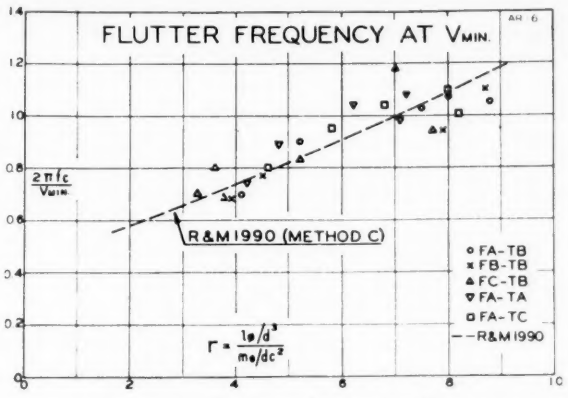


FIGURE 43. The flutter frequency at V_{min}.

and, because of recent dynamic failures of undercarriages, there was an interest in the rate of increase of these loads. Data was also to be obtained on the loads arising from man-handling when attempts are made to unstick skis which have become frozen to the ground. Finally, ski loadings, with special reference to the nose, were to be determined during landing operations.

The tests were all made with a Noorduyn Norseman Mk. VI aircraft over three successive winters, beginning in 1946-47. During the first winter two types of ski were examined, the first a U.S.A.F. type with a black iron bottom and the second, a Noorduyn Bear Paw type with a brass bottom. Electrical strain gauges were cemented to five selected stations on the skis and were calibrated in the laboratory. These strain gauges were used to determine the lengthwise loading on the skis by differentiation of the bending moment diagrams. Several bending moment diagrams were obtained which were found to differ considerably from the I.C.A.O. requirements, particularly in the region of the nose of the skis. Data was secured for both ice and snow surfaces (Fig. 45 shows the typical landing response of a ski).

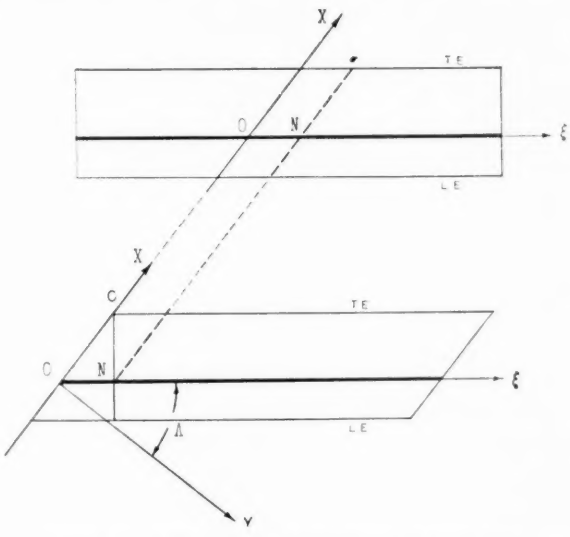


FIGURE 44. Reference axes in the theory of swept wing deformation.

Cracks developed in the U.S.A.F. skis so these were replaced, for the second winter's work, by a pair of North West Industries skis with a brass bottom. In the second year's work[56] the main effort was concentrated on the measurement of the loads transmitted to the undercarriage. This was effected by the employment of a special load measuring ski pedestal designed by the Structures Laboratory and fitted to one of the skis of the Norseman. The oleo-leg reaction was transferred by the axle to a weighing platform, suspended and restrained in its motion by weigh bars. The axial loads in these bars were indicated by calibrated resistance strain gauges mounted on each bar. The pedestal measured the vertical load, the drag load, the side load and the torque load on the ski. It was, of course, essential, during the landing load measurements, to record, simultaneously, the behaviour of the aircraft as defined by the forward and vertical components of its velocity, its roll, pitch and normal accelerations and the angles of bank and pitch. Horizontal velocity was determined by a photo-theodolite. Vertical velocity was expected to be difficult to measure and such was found to be the case. It was obtained by two methods; the first consisted in taking moving pictures from the aircraft, with a camera pointing vertically downwards, of a pattern of parallel lines 6 in. apart "painted" on the snow landing surface[57]. The second method was

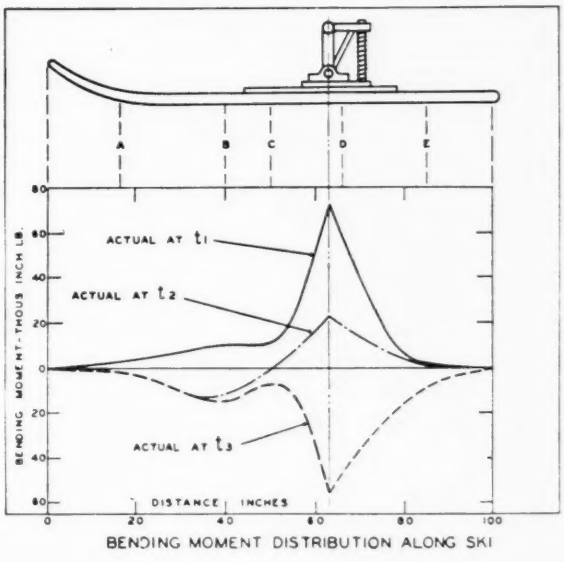


FIGURE 45. Typical response of a ski at the landing impact.

by the use of the photo-theodolite. Later, still a third method was developed, using a ciné camera mounted on a sledge, to photograph the aircraft from the rear. Accelerations were measured by suitably mounted accelerometers, while pitch and roll angles were measured by damped pendulums. A visual glide path indicator was provided which enabled the pilot to judge his approach to give, as closely as possible, the desired vertical velocities in the tests.

The limited data obtained in this programme referred to a restricted range of vertical velocities and snow conditions and could not therefore suffice for the derivation of conclusions applicable to the general design cases for skis. During the third winter's work[58] the experiments were extended to cover a wider range of snow conditions, including those encountered at Churchill, with further instrumentation to include load measurements on two skis. This extension of the work provided a greatly increased number of records in different localities with correspondingly greater statistical significance. The main aim of the work was to accumulate data on the maximum pedestal loads encountered. While it is not possible to recapitulate here all the results from Ref. 58, some idea of the magnitude of the loads can be given. The two skis tested had widths of 21 in. (A) and 32 in. (B) with corresponding contact lengths of 68 in. and 87 in. The maximum component loads recorded are shown in Table I.

It can be seen from this table that very severe vertical loads can result occasionally from landings on undulating snow surfaces encountered north of the tree-line (*e.g.* at Churchill). The highest torque load on a ski may be produced by man-handling, when a transverse load is applied at the tail of the aircraft to unstick a frozen ski.

TABLE I

MAXIMUM COMPONENT LOADS ON SKIS

Load	*Maximum values*	
	A	B
Vertical	11,190 lb.	13,590 lb.
Drag	2,390 lb.	2,630 lb.
Side	1,740 lb.	3,480 lb.
Torque	1,860 lb. ft.	3,020 lb. ft
Man-handling Torque	3,360 lb. ft.	——
Maximum vertical load due to impact with snow hummock during landing run (Churchill)	23,390 lb.	——

The Protection of Aircraft and Engines Against Ice Deposition

The interest of the N.R.C. in aircraft de-icing goes back for twenty years, the very first experiments being made in 1935. Four years later, Trans-Canada Air Lines were trying to improve the flow pattern given by the alcohol spray systems which they were employing to remove ice formations on propeller blades. It was realised by all concerned at that time that if engines and propellers could continue to function at full effectiveness, much of the hazard associated with flying under icing conditions would be removed or minimised. The N.R.C. decided that the use of heat, provided electrically, would in all probability be the most efficient and practical way of giving protection to the propellers. The early efforts were accordingly directed mainly at solving this problem by the development of conducting rubber "shoes" for the propeller blades and hub generators to provide the power. Simultaneously, attention was being given to the meteorological conditions which are present when icing occurs. Knowledge was slowly accumulated and much experience was gained on the kind of icing which was likely to occur under various meteorological conditions and its duration and severity. With the exception of some ground tests, using water sprays to simulate icing, all the experimental work was done while flying in icing conditions.

By 1946 the practicability of the electro-thermal method of propeller de-icing had been demonstrated and the design and proving of a suitable hub generator had been completed[59]. With the anticipation of the industrial development of larger capacity aircraft generators, work was started on the adaptation of brush and slipring assemblies which, it was felt, would eventually replace the hub generators. In the post-war period the "cyclic" application of the heating power was adopted and perfected, using the power from the aircraft generator with a minimum increase in generator capacity and a considerable saving in weight. When the RY3 aircraft, which had been donated by the Ministry of Aircraft Production, was retired in 1948, a North Star aircraft was offered for the work by the R.C.A.F. This permitted the introduction of new and improved propeller heater elements for the conduct of more refined experiments on anti-icing and de-icing. Through this work it was possible to improve the propeller pads to give higher temperature tolerance, resistance against erosion and, light weight, combined with good thermal and electrical properties.

Electro-thermal wing de-icing was also developed in the post-war period. Wing pads made both of conducting rubber and woven resistance wire were applied on the RY3 aircraft which was equipped with a 250 volt, 20 KVA power supply for the wing de-icing tests. The woven wire type of element showed to advantage in comparison with the conducting rubber type on the score of control and stability of resistance. It was unsuitable, however, for propeller blades because of the double curvature surfaces involved. When the North Star came into service it was equipped with a special Shark's fin for the testing of wing de-icing schemes. Flight tests were supplemented by experiments in the new icing tunnel, and in the development of the "cyclic" system of ice shedding the experimental work was accompanied by theoretical studies[60] of the transient heat flow problem. The tunnel permitted systematic studies in which the variation of specific power, temperature, liquid water content, speed and incidence could be provided. This work demonstrated the economy of high specific power inputs and the importance of correctly positioning the so-called "parting strip" heater on the nose of the wing in relation to the stagnation line of the air flow. All this work,

completed in 1952, provided a basis for the rational design of thermal wing de-icing systems, with the tunnel and theoretical work being checked by flight tests.

Since a de-icing system will only work at highest efficiency when carefully controlled and since the heat requirements depend on a number of independent variables, fully automatic control is likely to give the greatest satisfaction. Such a control system was developed, first to operate on the pneumatic wing de-icer, and following success with that it was further developed and applied to thermal-electric systems. This control operates on a signal from an ice detector (preferably an orifice type[61] which can distinguish between light and dangerous types of icing). The length of the heating time, in the cyclic method of de-icing, is set by the ambient air temperature, the relation between air temperature and shedding time being known from flight experimental results.

The Aircraft Instrument Laboratory of the N.R.C. has contributed enormously to the success of the de-icing work by the development of special instruments for studying the meteorological conditions associated with icing and for indicating the presence and rate of icing. Many of these are described in Ref. 31. Probably the most important single parameter is the free water content of icing clouds. This is usually measured by the amount of ice collected over a known air path by an impactor exposed to the supercooled droplets. Ref. 31 discusses four methods for the measurement of water content. Instruments for the measurement of cloud droplet size and distribution and cloud density are also described. Finally, the problem of cloud temperature measurement is discussed and three special thermometers are described. At a later date a direct reading thermistor type thermometer was developed[62] which proved to be stable, rugged and accurate. The limitations of water content meters which depend on ice collection were studied[63, 64] and it was concluded that, until ice-accretion instruments embodying practicable refrigeration are developed, it will be necessary to use both a thermal method, which depends on the temperature drop of a hot body exposed to the icing, and an ice-accretion method. This is particularly true when dealing with clouds in which the free water content is high, or when the temperature or speed of flight is high. The orifice-type ice detector was developed, both as an indicator of icing[65] and as an icing-rate meter[66] and has proved itself useful as the controller for the automatic control of the entire de-icing system.

The value of hundreds of hours of flying in the provision of information on the meteorological conditions for icing cannot be over-emphasised. The data collected has been digested and issued in a form convenient both for the meteorologist and the designer of de-icing systems[67, 68]. The information presented refers mainly to liquid water content and temperature and the extent in miles over which such conditions may be met. The variation of droplet size with water content and air temperature is also included as a parameter of secondary importance which mainly influences the extent and type of icing.

The flight test work, in addition to the collection of meteorological data, the checking of laboratory experiments, and trials of various de-icing schemes, has permitted the measurement of drag due to icing and observations of the transient and steady temperatures in electro-thermal de-icing pads. For a general report on the work I could not do better than refer you to the paper read by Orr, Fraser and Milsum before the Fourth Anglo-American Aeronautical Conference in London in 1953*.

The first work on gas turbine icing was done in the engine laboratory during the winter of 1946-7 using a Junkers Jumo 004 engine with water spray nozzles in natural freezing temperatures to simulate icing conditions[69]. These experiments demonstrated that heavy ice formations could build up quite quickly on the starter motor fairing and on the compressor guide vanes. As much as 16 lb. of ice built up in one test on the starter fairing, causing extensive blocking of the compressor inlet with consequent loss of thrust and excessive tail pipe temperatures. Two compressors were stripped of blades by ice detached from the fairing, in one case, and the guide vanes in the other. The shape of the ice formation on the starter fairing was shown to be dependent mainly on the air flow configuration at the entry duct. Under simulated conditions it is difficult to reproduce exactly the flow conditions existing in flight.

There are three possible methods for the de-icing of turbo-jet engines, alcohol injection, charge heating and surface heating. Studies of the first method[70, 71] suggested that alcohol de-icing might require 3 per cent. extra tank capacity for half an hour protection and that an increase of up to 6 per cent. in thrust could be expected when using alcohol. With the increased air consumption of modern jet engines this requirement may underestimate today's needs.

Theoretical and experimental studies on the charge heating method were made in the spring of 1948[72] using the Jumo 004 engine under simulated icing conditions. Increasing the inlet temperature by 30°C. gave a 90°C. rise in jet pipe temperature and a 10 per cent. loss in thrust. The ring mixer employed to introduce the hot air failed to protect completely the starter fairing and some ice formed continuously on its foremost part. The heat required to keep the guide vanes free of ice at −6°C. was between 112 and 148 Centigrade heat units per second, about twice the amount calculated. Although the mixing of the hot gas with the intake air appeared to be reasonably good, the discrepancy between theory and experiment might have been due to incomplete mixing.

Anti-icing by surface heating requires the addition of heat to all areas where ice tends to form, including the starter motor fairing, the inlet guide vanes, the spider and the stator and rotor blades. Ice deposits on the rotor blades were observed in later tests at the N.R.C. and this is to be expected in flight during such conditions

*Aircraft De-icing by Thermal Methods. J. L. Orr, D. Fraser, and J. H. Milsum. *Fourth Anglo-American Aeronautical Conference*. Royal Aeronautical Society, 1953.

as idling descent through icing clouds. Electrically-heated shoes were fitted to the starter fairing and spider and some tests were made. Analysis of the results indicated a need for improved heaters to reduce the thermal losses. Subsequently, a complete electro-thermal system was designed for application to all the appropriate surfaces. Due, however, to the heavy load on the aircraft generating capacity, such a system is not tolerable. A hot gas system, using air from the last stage of compression, was also designed and tested in the icing tunnel and gave considerable promise.

I am glad to say that this work is continuing with Ministry of Supply support.

The Augmentation of Jet Engine Thrust by Reheat

During the 1939-45 War the Junkers Company developed a reheat scheme in which the fuel was injected upstream of the turbine blades. By the time the fuel reached the jet pipe it had become heated sufficiently to burst into flame spontaneously, without the necessity for any flame holder. With modern engines of higher gas velocities the direct application of the Junkers system has been unsuccessful.

In 1951 the N.A.E. began experimenting with this reheat system. The first tests were done with a Jumo 004 engine and were extended later to a Derwent V and a Goblin II. It was found that the system could be made to function if part of the reheat fuel is injected ahead of the turbine and if steps are taken to stabilise the flame in the jet pipe. The system permitted an augmentation of the normal static thrust of the order of 30 per cent. in the case of the Derwent V engine. In addition, the cooling of the turbine blades by the impinging fuel opened up the possibility of increasing the basic rated thrust by burning additional fuel more economically in the combustion chambers and over-speeding the turbine.

The progress of the work demanded the completion of a number of separate investigations. One of the major difficulties was to secure stable combustion and some time was spent in studying the destructive vibratory phenomenon of howling combustion[73], which occurs under certain reheat conditions, using first a small-scale test rig and, later, the tail pipes of Derwent and Jumo engines. Various methods were studied for stabilising the flame in the jet pipe. A baffle (or baffles) to achieve stability was examined by Golitzine[74]. Such a scheme is not new, but the novel feature in this case was the need to achieve stability when using a non-homogeneous mixture of liquid fuel and air. Previous applications have been concerned with homogeneous gaseous fuel and air mixtures. Baffles have the disadvantage of high drag and are also suspected of contributing to the initiation of howling combustion. The upstream, air blast injection of kerosine fuel was considered[75, 76] as an alternative means of flame stabilisation. Experiments indicated that it was possible to secure stability in exhaust gas velocities up to about 500 ft./sec. by this means. It was important to know how much blade cooling was achieved by injecting fuel upstream from the turbine. Blade temperatures were accordingly determined by observing the hardness of calibrated steel pellets inserted in the blades before a test run. In connection with the behaviour of the injected reheat fuel, the disruption of liquids in an air stream[33] was examined and some aspects of the mechanism of blade cooling were given preliminary study, both theoretically and experimentally[36]. These two pieces of work have already been discussed earlier in this report.

Through the co-operation of the Ministry of Supply a Gloster Meteor aircraft was made available for flight tests. A great deal of ground running was therefore done on the Derwent VIII engine to adapt the reheat method to this power plant, to develop a control system and to prove the complete system. Flight tests have been eminently satisfactory with consistent lighting at altitudes of 35,000 ft. with tail pipe pressures of $4\frac{3}{4}$ lb./in.^{2}.

An Orenda XI engine, with two-stage turbine, was loaned by the R.C.A.F. and successful adaptation of the system to this engine was effected. Ground running has indicated no basic difference in this reheat operation when applied to a two-stage turbine.

The Aerodynamics of Missiles

During the past five and a half years a small aerodynamics group at the Canadian Armament Research and Development Establishment (C.A.R.D.E.) has been engaged in theoretical and experimental work in the missiles and ballistics fields. Many of the problems of guided missile aerodynamics have been attacked, using existing linearised theory. As an example, the use of differential full-panel deflections for the provision of aileron power when rectangular panels are arranged in a cruciform manner on a long cylindrical body, was studied[77, 78] both theoretically and experimentally. In the theoretical treatment account was taken of the wing-wing interference on damping in roll and aileron power. It was possible to compare the theoretical values of aileron power and damping in roll with experimental values derived from tests in the aero-ballistics range. The agreement in the case of aileron power was excellent but, where damping in roll was concerned, the agreement was excellent only if no wing-wing interference was assumed. This may be due either to over-estimation of the interference effects, or a contribution to damping in roll from the yaw cards used in the aero-ballistic range.

The investigation of aeronautical stability, performance, control and structural problems has also been attacked both theoretically and with analogue computors. The generalised equations of rigid body motion, including roll intercoupling terms and the aeronautical stability derivatives accounting for the contribution of roll to aerodynamic forces, have been simulated and solved using a Reeves Analogue Computor. The use of this computor has been extended to the problems of aeroelasticity and resonance. The possibility of aerodynamic, structural or control system resonance has been studied by simulation on the computor. Unfortunately, the results of these studies are all classified.

A description of the C.A.R.D.E. aero-ballistic range and the free-flight gun-launching technique is given in Ref. 77. C.A.R.D.E. armament firing ranges have also been employed for testing free-flight rocket-launched models, carrying scratch-recorder instrumentation, up to transonic speeds, with successful measurement of accelerations and pressures. These ranges are limited to 1,500 yards. A large firing range has been developed at Picton, Ontario[79], at which fairly large rocket-launched models have been tested up to Mach numbers of 2·5. The models flown have been fully instrumented to provide telemetred records of acceleration, pitch, yaw and roll angular velocities, pressures, temperatures and hinge moments. The free-flight trajectories are fitted, on the computor, to the theoretical equations of motion in order to check the estimated stability derivatives. This technique is a versatile and powerful one which lends itself not only to aeronautical development work but also to basic research work.

In this spirit do engineers, physicists concerned with thermodynamics, and the swarm of preoccupied draughtsmen tackle their work. In appearance, but only in appearance, they seem to be polishing surfaces and refining away angles, easing this joint or stabilizing that wing, rendering these parts invisible, so that in the end there is no longer a wing hooked to a framework but a form flawless in its perfection, completely disengaged from its matrix, a sort of spontaneous whole, its parts mysteriously fused together and resembling in their unity a poem."

Antoine de Saint Exupéry.

The Future

Plans are afoot in Canada to extend our research and testing facilities and to broaden still further the scope of our activities. At the Institute of Aerophysics, in Toronto, we shall explore the air flow characteristics associated with the very limits of the earth's atmosphere, using the new low density tunnel. Since the mean free path will be longer than the overall size of probing instruments, we shall be able to study complex flows not previously investigated. The major objective will be to abandon the continuum concept in favour of a unified molecular theory of fluid flow, which should prove more suitable for the analysis and description of the properties of strong shock waves.

We have had, for some considerable time, a requirement for a larger high-speed wind tunnel which could be used in aircraft and guided missile development work and which would be capable of reaching Reynolds numbers of 5 to 10 million. This tunnel, now in the design stage, will be constructed in Ottawa during the next three years. It will have a working section 5 ft. square and will cover a Mach number range of 0·2 to 4·5. It will be of the intermittent, blow-down type and it is hoped that its output will reach the same level as that of present continuous tunnels.

We are also cognisant of the fact that we are in urgent need of new facilities to assist in the development of aircraft power plants and new structural testing equipment of larger size and greater scope and flexibility. We hope to see a steady increase in the opportunities for aeronautical training and education in Canada and in the quality of this training. I believe that Canada will continue to make important contributions to aeronautical development. In the past decade we have exhibited a deeper interest in fundamental research in the aeronautical sciences and, to a limited extent, we have indulged this interest both within the universities and in Government laboratories. I sincerely hope that this interest will grow and flourish and that it will be productive of results of which Canadians can be as justly proud as they now are of their more practical accomplishments in aviation.

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76. GOLITZINE, N. (1955). Flame Stabilization in the Exhaust Reheating of a Jet Engine Using Upstream Air Blast Injection of the Fuel. N.A.E. Laboratory Report LR-126, 1955.
77. BULL, G. V. and TIDY, G. H. (1953). Analysis of the Effect of Wing-Wing Interference on the Rolling Characteristics of Cruciform Rectangular Wing-Body Combination in Steady Supersonic Flow. Canadian Armament Research and Development Establishment, C.A.R.D.E. Report No. 293/53, December 1953.
78. BULL, G. V. (1955). Some Aerodynamic Studies in the C.A.R.D.E. Aeroballistics Range. C.A.R.D.E. Miscellaneous Report No. 53/55, May 1955.
79. CHINNICK, R. F. (1954). The C.A.R.D.E. Test Range at Point Petre. C.A.R.D.E. Technical Memorandum No. 113/55, December 1954.

MR. E. T. JONES, C.B., O.B.E., F.R.Ae.S. (President-Elect) proposed the vote of thanks:—

To prepare 22,000 words and 45 figures was in itself a somewhat momentous achievement but Dr. Green had done much more than that. He had given them an aeronautical classic on Canada, one that should live for many years, and he had delivered it in about 50 minutes in a most masterly fashion. To him, this had been an education. There were many things in Dr. Green's paper which he knew and there were some that he did not. He knew, for example, that Dr. Rupert Turnbull had done a lot of work on constant speed propellers, and he knew too, that he was an aeronautical enthusiast, but he had overlooked the fact that he had built a tunnel in Canada in 1902.

There were probably other things which some of them had overlooked. Dr. Green had mentioned that Canada did much intensive flying in the last War, by taking part in the British Commonwealth Air Training Plan. They did a lot of work, he had told them, on balancing controls, repeatability of control performances, de-icing work, cold weather tests on engines, cold weather operational work on complete aeroplanes, and he had said that because of the concentration of work in these operational fields Canada had not made much contribution in the field of research.

He did not think that many of them realised the way in which the Canadian research and development staff was so fully employed on war time development work. It was interesting to see that Canada had embarked on a post-war research programme of some magnitude. Those who had seen Dr. Patterson's work in Toronto on shock tubes and had the pleasure of listening to him at the Anglo-American Conference in Los Angeles, knew that his work in that field was second to none. They knew too that McGill University's work in gas dynamics, the N.R.C. work in fluid droplets which they had seen that night, were also pretty well second to none and it was interesting and encouraging to note that they were proposing to expand their fundamental research work. He thought also that it had had an impression on the aircraft industry in Canada. It was not in the scope of the paper, he knew, but the Canadian Industry was flourishing tremendously and he had no doubt it had been partly the result of the more forward planning that was taking place in research in general.

He knew there was no discussion on these named lectures but had there been, he would have put one question to Dr. Green. Dr. Green, since 1948, had been the Canadian delegate to the Commonwealth Advisory Aeronautical Council. Since 1951 he had been the Canadian delegate on A.G.A.R.D. within N.A.T.O. and he had been in Canada working on research and development for 26 years, yet Dr. Green made reference to about 66 other people who made contributions, and in modesty he did not make reference to anything he had done himself, which he though could not be right. Many of them had known Dr. Green for many years and he thought he should give Dr. Green the British equivalent to the Canadian understanding of the accuracy of the bomb sight mentioned in the paper. Dr. Green said it was so accurate that a bomb could be placed in a pickle barrel, but their impression was that a peanut could have been dropped on a spike.

He had very great pleasure in proposing this vote of thanks to Dr. Green.

Following the Lecture a dinner was given by the Council of the Society at which the following were present:—

Dr. A. M. Ballantyne, T.D., B.Sc., Ph.D., A.F.I.A.S., Hon.F.C.A.I., A.F.R.Ae.S., Secretary of the Royal Aeronautical Society. Air Commodore F. R. Banks, C.B., O.B.E., M.I.Mech.E., F.Inst.Pet., F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Director, Bristol Aeroplane Co. Ltd. Professor A. D. Baxter, M.Eng., M.I.Mech.E., F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Professor Aircraft Propulsion, College of Aeronautics, Cranfield. Mr. R. J. Brearley, M.B.E., Scientific Liaison Officer, National Research Council of Canada. Sir John S. Buchanan, C.B.E., A.M.I.Mech.E., F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Chairman, London and South-Eastern Regional Board for Industry. Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S., Member of Council and Honorary Treasurer of the Royal Aeronautical Society; Director of Construction and Research Facilities, Ministry of Supply.

Sir Sydney Camm, C.B.E., F.R.Ae.S., Past President of the Royal Aeronautical Society; Director and Chief Designer, Hawker Aircraft Ltd. Air Commodore G. Carter, C.B.E., A.F.R.Ae.S., President, New Zealand Division Royal Aeronautical Society. Sir George Cribbett, K.B.E., C.M.G., 1950 Lecturer; Deputy-Secretary, Ministry of Transport and Civil Aviation. Captain Norman Croucher, London Manager, Australian National Airways Pty. Ltd.

Mr. E. Ll. Davies, Defence Research Member, Canadian Joint Staff. Mr. Handel Davies, M.Sc., A.F.I.A.S., F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Scientific Adviser to the Air Ministry. Lord Douglas of Kirtleside, G.C.B., M.C., D.F.C., Chairman, British European Airways Corporation.

Mr. G. R. Edwards, C.B.E., B.Sc., F.R.Ae.S., A.M.I.Struct.E., Vice-President of the Royal Aeronautical Society; Managing Director, Aircraft Division, Vickers-Armstrongs Ltd.

Sir William S. Farren, C.B., M.B.E., M.A., F.R.S., M.I.Mech.E., Hon.F.I.A.S., F.R.Ae.S., Past President of the Royal Aeronautical Society; Technical Director, A. V. Roe & Co. Ltd. Sir Wilmot Hudson Fysh, K.B.E., D.F.C., M.Inst.T., F.R.Ae.S., F.R.G.S.(Aus.), 1945 Lecturer; Chairman Qantas Empire Airways Ltd.

Mr. G. W. H. Gardner, C.B., C.B.E., B.Sc., M.I.Mech.E., F.R.Ae.S., Director-General of Technical Development (Air), Ministry of Supply. Mr. H. H. Gardner, B.Sc., F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Chief Designer, Guided Weapons, and Special Director, Vickers-Armstrongs Ltd. Dr. J. J. Green, M.B.E., B.Sc., A.R.C.S., D.I.C., F.R.Ae.S., F.I.A.S., F.C.A.I., 1955 Lecturer; Defence Research Member Canadian Joint Staff, Washington.

Sir Arnold A. Hall, M.A., F.R.S., F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Director, Royal Aircraft Establishment. Mr. R. E. Hardingham, C.M.G., O.B.E., F.R.Ae.S., 1952 Lecturer; Secretary and Chief Executive to the Air Registration Board. Mr. P. A. Hearne, D.C.Ae., D.L.C., Grad.R.Ae.S., Member of Council of the Royal Aeronautical Society; Project and Development Branch, B.E.A. Engineering Base.

Mr. E. T. Jones, C.B., O.B.E., M.Eng., F.R.Ae.S., President-Elect of the Royal Aeronautical Society; Principal Director of Scientific Research (Air), Ministry of Supply. Air Marshal Sir Owen Jones, K.B.E., C.B., A.F.C., B.A., D.I.C., M.I.Mech.E., F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Controller of Engineering and Equipment, Air Ministry. Dr. W. P. Jones, M.A., D.Sc., F.R.Ae.S., A.F.I.A.S., Superintendent, Aerodynamics Division, National Physical Laboratory.

Mr. C. W. Labette, A.F.R.Ae.S., Past President, New Zealand Division Royal Aeronautical Society; Engineering Superintendent, New Zealand National Airways Corporation. Mr. B. P. Laight, M.Sc., A.M.I.Mech.E., A.F.R.Ae.S., Member of Council of the Royal Aeronautical Society; Chief Designer, Blackburn and General Aircraft Ltd.

Mr. P. G. Masefield, M.A., F.I.A.S., F.R.Ae.S., Vice-President of the Royal Aeronautical Society; Chief Executive, British European Airways Corporation. Mr. E. J. May, London Traffic and Sales Manager, Trans-Canada Air Lines.

Mr. I. H. G. Nicholson, A.M.I.Mech.E., A.M.I.A.E., A.R.Ae.S., Vice-President, Southern Africa Division, Royal Aeronautical Society.

Mr. J. J. Parkes, A.F.R.Ae.S., President, Society of British Aircraft Constructors Ltd. Colonel R. L. Preston, C.B.E., A.F.R.Ae.S., Secretary-General, Royal Aero Club. Captain J. L. Pritchard, C.B.E., Hon.F.I.A.S., Hon.F.R.Ae.S., M.R.I., Secretary of the Royal Aeronautical Society, 1925-1951.

Mr. N. E. Rowe, C.B.E., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S., President of the Royal Aeronautical Society; Technical Director, Blackburn and General Aircraft Ltd.

Cpatain R. B. Tapp, London Manager, Qantas Empire Airways Ltd. Mr. J. H. Tudhope, Civil Aviation and Communications Attaché to the High Commissioner for Canada.

Sir Hubert Walker, C.B.E., M.I.C.E., 1953 Lecturer. Flying Officer K. Weinstein, A.F.R.Ae.S., Royal Canadian Air Force. His Excellency The Hon. Sir Thomas White, K.B.E., D.F.C., V.D., High Commissioner for Australia. Mr. H. A. Wills, B.E., F.R.Ae.S., Assistant Controller, Research and Development (Department of Supply), Melbourne.

Reduction of Airline Costs

by

HEDLEY S. CRABTREE, M.A., A.F.R.Ae.S., A.M.I.Mech.E.

PART I

THE BACKGROUND

1. Introduction

Sir William Hildred, C.B., O.B.E., Director-General of I.A.T.A., in his Annual Report, which he presented at the I.A.T.A. Conference in Paris in the middle of September 1954, pointed out that there was an urgent need for a drive for greater efficiency to obtain a balanced airline economy. He quoted some interesting I.C.A.O. figures. These covered all the world's scheduled operators, both the profit-making and the loss-making companies. In 1951, the world's airlines showed that total operating revenues were 6 per cent. higher than total costs. In 1952, this figure was down to 3·6 per cent. and in 1953, down to 1·1 per cent., which represented $27-million profit on a total business of $2,500-million. It should be noted that this $27-million profit is arrived at after the pay-out of direct taxation by the profit-making companies to the tune of $69-million.

There is unanimity among the airlines of the world that total costs must be reduced, and for some airlines it is a requirement of some urgency.

An analysis of several airlines' costs shows that the operating portions of the costs are in excess in total of all other costs. (*See* Fig. 1).

The remaining costs, which are usually the lesser portion of the total costs, are normal commercial costs, such as sales, head office administration, traffic handling, advertising, agency fees, etc., etc., and their progressive reduction is held to be within the confines of good commercial management and is not dependent upon any specialised engineering knowledge or experience.

The purpose of this paper is to study the present practices of airline operation, and particularly to investigate the possibilities of reductions of technical costs.

2. Nomenclature

The following terms are used throughout this paper:—

(*a*) *Classification of operators*

Short-Haul, in general operating routes with stages of under 750 miles, normally with twin-engined aircraft.

Long-Haul, in general operating routes with certain stages in excess of 750 miles, always with four-engined aircraft.

Mixed Long and Short-Haul, operating both long and short-haul stages as defined already, and equipped with both twin and four-engined aircraft.

(*b*) *Classification of aircraft*

Medium-Range, maximum take-off weight not exceeding 80,000 lb. *OR* with a theoretical "nil wind" to empty tank range not exceeding 2,400 miles.

Long-Range, maximum take-off weight exceeding 70,000 lb., and a theoretical "nil wind" to empty tank range exceeding 2,400 miles.

(*c*) *Classification of fleet strength*

Small Fleet, consisting of not more than eight aircraft of any one type.

Medium Fleet, consisting of more than eight aircraft and less than sixteen aircraft of one type.

Large Fleet, consisting of more than sixteen aircraft of any one type.

3. Definition of Operating Costs

For the purposes of this paper, the following costs are considered as "operating costs."

(*a*) *Engineering*

All maintenance and overhaul costs, including engineering management, supervisory and direct labour staff costs; all aircraft spares and other stores consumed by the Engineering Department; all rents, rates, heating and lighting costs of engineering facilities; all engineering equipment depreciation and upkeep costs, all sub-contracting of engineering work to outside firms, and all other incidental engineering overhead costs, such as labour management, office, purchase and store-keeping staffs, telephones and cables, technical education, travelling and allowances, printing, stationery and office equipment costs.

(*b*) *Operational*

All salaries and expenses of operational management, of pilots and other crews and of all operational staff, including all operational despatchers, line inspectors, instructors, all training and educational costs; uniforms, medical costs, charts, all ground-to-air operational telecommunications costs, and all other incidental operational costs, such as offices, telephones, heating, lighting, travelling and travel allowances, medical services, stationery and office equipment costs.

(*c*) *Fuel and Oil*

All fuel and oil costs.

(*d*) *Aircraft Depreciation*

All aircraft depreciation costs, including depreciation of aircraft spares.

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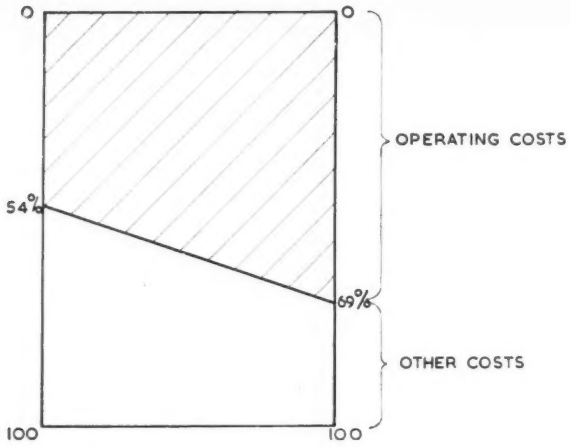


FIGURE 1. Airline costs.
Figures taken from a number of representative airlines.

4. The Relationship of Operating Costs to Total Costs

Figure 1 shows that operating costs vary from 54 per cent. to 69 per cent. of total costs, for a number of representative airline companies, covering long-haul, mixed long and short-haul, and short-haul companies.

Figure 2 shows the variations in percentage of total cost of the four main operating cost items.

The highest average cost of the four different operating costs shown in Fig. 2 is for engineering, and this figure shows as between companies a large variation.

Of the engineering costs, the two single highest items are the staff costs and the spare parts costs.

Among the more efficient operators, the engineering staff and labour costs (assuming in each instance that engineering staff includes the Chief Engineer and all technical staff, as well as technical buying staff, stores staff and engineering labour management staff) account for about 33⅓ per cent. of all engineering costs, while spares account for 40 per cent. - 50 per cent., and the remainder represents all other engineering costs. Thus engineering staff and labour costs may be expected to account for from 5 per cent. to 10 per cent. of the total costs.

If the human engineering effort expended per aircraft hour flown is examined, by adding together all the man-hours worked by all the engineering staff, from the Chief Engineer downwards and including all the direct labour man-hours, and this figure is then divided by the total aircraft hours flown by the company's fleet, a variation of engineering human effort is found as between the most efficient scheduled operators and the least efficient, of close on four to one. Even allowing for differences which exist due to variations of utilisation, size and types of fleets, type of operations, and remembering that the great bulk of operators today are operating very similar aircraft, this variation indicates that there is a vast difference in economic and engineering efficiency as between different operators.

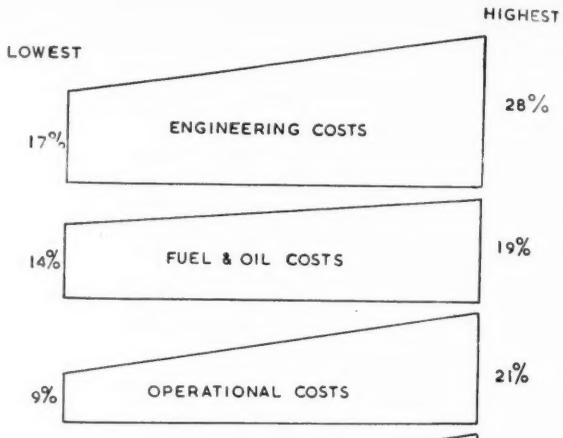


FIGURE 2. Operating costs.
Expressed as percentage of total costs.

The difference in efficiency will not only affect engineering labour and staff costs and other engineering costs, as already defined, but will also have an indirect bearing upon the costs of other Departments outside the Engineering Department.

The variation in total human effort to produce a capacity-ton-mile of work as between different companies in the same category only bears out this contention that, in the air transport companies of the world today there is a vast difference in the degrees of efficiency of management and operation. It is not possible to make a strict comparison between the capacity-ton-mile per employee figures of different companies, for varying and obvious reasons. Nevertheless, those companies returning the highest output per employee (*i.e.* Companies F to J, Fig. 3) overhaul all their own equipment and do not resort to any sub-contracting of their engineering work; whereas those companies returning lower output per employee do not in all instances overhaul their own equipment.

LONG-HAUL		CAPACITY TON-MILES PER EMPLOYEE
OPERATOR	A	21,950
OPERATOR	B	21,100
OPERATOR	C	13,370
OPERATOR	D	8,680
OPERATOR	E	7,135
SHORT-HAUL		
OPERATOR	T	10,500
OPERATOR	U	6,535
OPERATOR	V	5,110

MIXED LONG AND SHORT-HAUL		CAPACITY TON-MILES PER EMPLOYEE
OPERATOR	F	24,150
OPERATOR	G	21,800
OPERATOR	H	19,620
OPERATOR	J	18,700
OPERATOR	K	17,130
OPERATOR	L	14,320
OPERATOR	M	11,480
OPERATOR	N	11,430
OPERATOR	O	8,950
OPERATOR	P	8,610
OPERATOR	Q	8,020
OPERATOR	R	7,230
OPERATOR	S	7,220

FIGURE 3. Man power and production.

PART II
THE PROBLEM

5. Airline Engineering

Airline operation starts in the Engineering Department. It is here that aircraft should first be evaluated and recommended for purchase. It is here that the basic methods of operation are laid down. It is here that they are maintained and overhauled and made available for flying and thus, for earning revenue.

Experience has shown that an airline can only be as efficient as its Engineering Department. Upon the efficiency of the Engineering Department depends, to a very large extent, the ultimate safety of operations reached, the regularity of services flown and, to a lesser extent, the final economic result of the operator.

6. Historical

It is necessary to recapitulate briefly the history of the development of airline maintenance and overhaul.

Going back to the " stick and string " days, maintenance and overhaul was undertaken by a group of mechanics who inspected aircraft after flight and corrected the numerous failures and leaks and tightened up the parts found loose. Finally, their corrective work was inspected by a senior mechanic who was responsible for the certification of the work done.

Later, the inspection of aircraft after flight was taken over by separate " inspectors " who raised " snag lists " of work to be done.

The introduction of the more durable structures of metal aircraft made possible higher utilisation and led to the start of development of auxiliary and ancillary equipment with a serviceability at least equal to the improved basic structure. This resulted in further major developments.

In the first place, it became apparent that components could be given a " service life," being removed for overhaul at certain periods, with reduced maintenance between overhauls while installed on the aircraft. Then it was seen that taking an aircraft off service for a lengthy period once a year could be improved upon. This was first done by carrying out the overhaul by sections coincident with other work, taking the aircraft off service for a number of shorter periods within the calendar year. This was known as " progressive overhaul."

As utilisation mounted and experience was gained of the " lifeing " of components, it was seen that the calendar year had lost validity as the reference point for complete aircraft overhaul. Experience showed that some structure and components required overhaul well within a calendar year, on the basis of hours flown and work done. Other parts of the aircraft were found not to require overhaul for perhaps 3,000 or 6,000 hours flying, representing perhaps two or three calendar years' operation.

Thus were introduced " scheduled overhauls " related to hours flown; this procedure has been further developed and is still being developed.

It is now seen that the work done during maintenance and overhaul has been split up into " foreseen routine work " and " unpremeditated rectification work." It has been found possible, by statistical analysis, steadily to increase the proportion of "foreseen work" and decrease the proportion of " rectification work."

" Foreseen work " can be completely planned before it is started, and full work preparation can be made before the physical work starts. In other words, it is now possible to apply the most modern methods of repetitive production technique to an ever-increasing percentage of the necessary physical work to maintain and overhaul a fleet of aircraft.

Where such methods have been soundly adopted, two results have occurred at one and the same time. A far higher quality of work has been obtained and, as a result, accidents, service irregularities and technical incidents have been reduced, while at the same time the total engineering man-power per aircraft hour flown has steadily declined.

Such is a brief history of the development of the technique of maintenance and overhaul. It can be said today that some companies are way ahead in the lead of the scientific approach to this work, while some others are not far off the " stick and string " era! This is one explanation of the variation in engineering man-power costs already mentioned.

7. Management Responsibilities

An analysis of the work to be done to produce and sell air transport shows five separate responsibilities coming under Management.

These must be organised and operated in some way suitable to each company.

(*i*) Finance.
(*ii*) Engineering.
(*iii*) Operations.
In passing, it can be said that the two responsibilities of Engineering and Operations are essentially the production element of an air transport company.
(*iv*) Sales.
(*v*) Traffic.

Experience shows that, where a direct form of management is in existence, it places these responsibilities within separate Departments, so that a great many of the world's airlines have a simple basic organisation which can be tabled out as in Fig. 4.

It goes without saying that responsibility must be matched by authority and therefore both the Chief Engineer and the Operations Manager would be expected to have full and direct authority over all Sections and Divisions of their own Departments.

The Chief Engineer should have full responsibility for all the engineering costs as detailed in paragraph 3(*a*). As he should be the authority which will give the final technical advice on the selection of new aircraft, he should also accept responsibility for the depreciation costs of the fleet and spare parts. As his engineers will be responsible for all aspects of work on the engines,

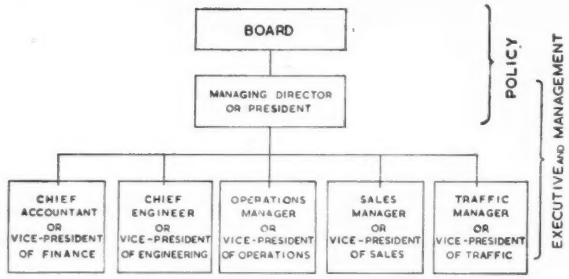

BOARD
MANAGING DIRECTOR OR PRESIDENT
POLICY
EXECUTIVE AND MANAGEMENT
CHIEF ACCOUNTANT OR VICE-PRESIDENT OF FINANCE
CHIEF ENGINEER OR VICE-PRESIDENT OF ENGINEERING
OPERATIONS MANAGER OR VICE-PRESIDENT OF OPERATIONS
SALES MANAGER OR VICE-PRESIDENT OF SALES
TRAFFIC MANAGER OR VICE-PRESIDENT OF TRAFFIC

FIGURE 4. The management.

for their safety of operation, and hence must lay down the technical standards of operation, he should also accept responsibility for fuel and oil costs. The Operations Manager should accept full responsibility for all operational costs, as already defined.

It is thus established that two responsibilities—or two Departments (*i.e.* Engineering and Operations Departments)—are responsible in air transport, directly or indirectly, for at least one-half of the total costs.

8. Engineering Policy

The policy to be followed by the Chief Engineer on an airline will be formulated by the Board and Management of a Company. It seems that such a policy can have but three aims:—

(*a*) Safety and regularity.

(*b*) Low cost of work done.

(*c*) Low elapsed time of doing work necessary.

(*a*) Safety is self-evident. No airline that is to maintain its position today can afford accidents. Moreover, quite apart from the adverse public effect of accidents, all technical irregularities, from the minor incident which causes a late departure, up to the major incident which may lead to a catastrophic accident, cause added and unforeseen costs, by no means limited to the Engineering Department.

(*b*) Low costs should be the next aim.

(*c*) *Low elapsed time of work* is also vital, since this, if achieved, will enable higher aircraft utilisation to be obtained and lower capital costs in rotatable spares to be obtained. For instance, the percentage of spare engines to installed engines varies among operators from 50 per cent. to nearly 150 per cent. This on a large fleet of, say 20 long-haul aircraft can represent today a difference of £1-million invested in spare engines alone. Applying this variation of percentage spares to installed units throughout all the multitudinous and high-costing equipment of a modern high-speed transport fleet, it will quickly be found that the variation in capital invested in equipment can be considerable.

Thus low total engineering costs are directly coupled with low elapsed times of work procedures.

9. Work Control

If low costs are to be obtained in airline engineering, thinking must start with the consideration of direct labour costs.

Effective use of direct labour depends primarily upon the possibility of being able to give, ahead of the work starting, accurate and simple instructions for the work required. If this can be achieved, it follows that it will be possible to arrange the immediate availability at the place of work of all the facilities required by the worker, *i.e.* special tools, spares, ground equipment and instructions, as well as a high standard of training for key workers.

10. Work Planning

Airline maintenance and overhaul must be regarded as merely production work. The whole of the work is made up of several thousands of different jobs, repeated at varying intervals and in varying sequence, year in and year out. The more frequently a job is repeated, the more carefully must it be planned to get down to the least possible labour effort needed to do it in the least possible elapsed time.

Before any work can be planned, it is necessary to establish clearly what requires to be done. The old method of using inspectors to find out what should be done is today seen to be increasingly unsatisfactory for several reasons. Firstly, modern production methods demand accurate advance knowledge of all work to be done. A shop inspection report made immediately before work starts is too late. Secondly, the amount of work that will result from such inspectors will tend to vary with each inspector. Thirdly, the modern aircraft is becoming increasingly complicated and the technical knowledge necessary to judge reliability and safety is often beyond the limited technical training of a single shop inspector.

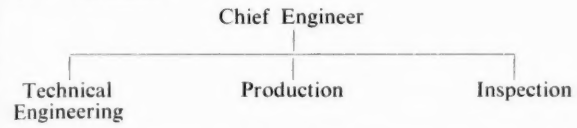
Fourthly, if elapsed times of maintenance and overhaul work are to be reduced down to a minimum, an inspection function which lies outside the control of producton is no longer practicable, and there must be developed a system that can be integrated into modern production techniques.

Fifthly, it is recognised that any and all rates of wear can be calculated. Where such calculations can be verified and backed up by accurate statistical records of actual rates of wear and failure, a high degree of accuracy in forecasting safe life can be obtained. Already, experience shows that, where such work is carried out by fully qualified engineers, backed up by an adequate and efficient system of technical recording and technical analysis, the amount of work that is required and the time at which it will become due, and particularly the avoidance of unnecessary work, can be more accurately established than by any other methods at present known.

PART III
MEETING THE PROBLEM

11. Engineering Organisation

In order to cover adequately these separate functions already mentioned, the organisation of an airline's Engineering Department can be conveniently split into three Divisions:—



The Technical Engineering Division or, as it is called throughout this paper, the Technical Division, can be likened to the thinking element; the Production Division to the physical work, or muscle element; and the Inspection to the security, or nerve control element.

The authority needed to drive, inspire and lead these three Divisions must be the Chief Engineer. His chief duty will be the preservation of a balance, both technical and economic, within the whole of the Engineering Department and relative to the general policy of his Board.

12. Measurement of Technical Efficiency

All engineering experience can, and must, be translated into suitable measures of efficiency. As regularity and safety are the first vital requirements, the most important measures of technical efficiency are naturally based upon technical irregularities.

1. *Major Troubles.* These can be classified as any technical troubles occurring on the ground or in the air which result in either a delay of over one hour to start a scheduled service, or an interruption of the plan of a scheduled flight. The unit of measure usually used is the number of incidents per 1,000 flying hours.

2. *Technical Late Departures.* These are usually classified as late departures of over five minutes and up to one hour caused by technical reasons at the airport where the incident occurred. The unit of measure usually used is the number of such incidents per 100 scheduled starts.

3. *Malfunctions.* These are classified differently from company to company, but it seems to be becoming general practice to count all irregular changes of equipment necessary at maintenance checks, as well as pilots' written reports reporting malfunctioning of equipment in the air, not already classified as major troubles. It is also necessary to count in unforeseen serious troubles that occur during both maintenance and overhaul. A pre-determined method of establishing the limitations of such troubles is essential. The unit of measure usually used is the number of malfunctions per 1,000 flying hours.

4. *Unpremeditated Engine Changes.* Because of the importance to safety of engine operation and the heavy costs that accrue as a result of unpremeditated engine changes, irregular engine change records are an important measure of efficiency. They are normally expressed as the number of unpremeditated engine changes per 1,000 aircraft flying hours, or per 1,000 engine flying hours.

5. *Unpremeditated Unit Changes.* Although these statistics, like the unpremeditated engine change rate, will fall into the categories of "major troubles," "technical late departures," or even "malfunctions," they are normally kept in addition to the aforementioned statistics.

These measures of efficiency, balanced against engineering human effort costs, and spare parts costs, are the only effective measures of efficiency. Their use is as essential to good Management as it is to the Chief Engineer of an airline and to the Chief of his Technical Division. These statistics are in fact essential tools of all airline engineers and especially the engineers employed in Technical Divisions where these measures will be used to establish priorities in their work effort.

13. Technical Engineering Division

Technical Divisions are having to be increasingly manned by qualified engineers who, in addition to a sound theoretical technical training, have had in their early careers thorough workshop training. Their responsibility is to lay down the basic requirements of maintenance and overhaul, so that at no time does the airline operate its aircraft or equipment in a dangerous condition or in a condition which will give rise to service delays and technical incidents, through breakdowns. Their original basis of work will be the recommendations laid down by the manufacturers of the aircraft, engines and equipment. But manufacturers do not themselves have direct operating experience and hence, as a new type of aircraft gets into service, it is the skill and knowledge of the Technical Division which will enable an operator to increase reliability and at the same time decrease maintenance and overhaul costs.

The sources of knowledge which the Technical Division can draw upon are fivefold:—

(*a*) The experience gained by the Operating Department, thrown up by the daily aircraft operational reports made out by flight crews.
(*b*) The conditions found and experience gained during overhaul of aircraft and components.
(*c*) The experience gained by the maintenance check work.
(*d*) Their own experience on previous types of equipment.
(*e*) Specialist knowledge gained from manufacturers, from design and research organisations and other specialists.

Of these sources, the operational and overhaul sources are by far the most important. It naturally follows that all the technical information required by the Technical Division must be quickly and accurately made available to them.

It is all too easy for an airline's technical team to concentrate on the current high spots of trouble and completely overlook the multitude of other trends and developments which are continually building up and

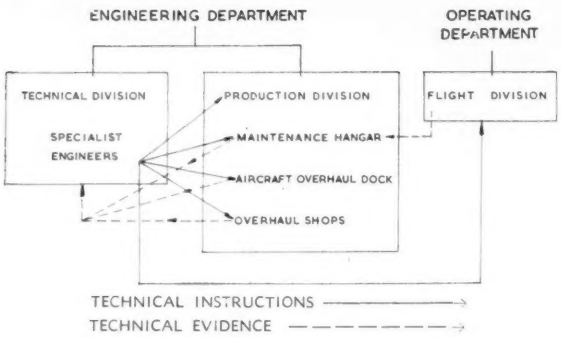


FIGURE 5. Generation of technical instructions.

which, if not checked and closely watched, may only too easily lead to crisis or even catastrophic conditions.

The continual analysis of all this information from these five sources should have two aims:—

(*i*) Preventive action.
(*ii*) Increased economy of operation.

The modern aeroplane is now calling for an increasing degree of specialised technical knowledge and, as a result, the Technical Divisions of airlines are having to split their technical work among a number of specialist engineers.

In a Company operating a medium or large fleet of advanced long-haul aircraft, it might be expected that the following different technical aspects would be covered by specialist engineers, each of whom would be technically fully qualified in his own subject:—

Chief Technical Engineer
Engine Engineer
Power-plant Engineer
Supercharger and Pressurisation Engineer
Propeller Engineer
Performance Engineer
Airframe Engineer
Airframe Undercarriage and Hydraulics Engineer
Airframe Pressurisation Engineer
Airframe Structures Engineer
Electrical and Instrument Engineer
Assistant and Electrical Engineer
Radio Engineer
Publications and Weight Control Engineer
Drawing Office Staff (5)
Publication issuing staff (3)
Engineering secretarial staff (5)
Special Investigation Engineer
i.e. Total staff, say, 28.

The sizes and the duties of Technical Division staffs vary enormously from company to company.

If a company operates a fleet made up of two different types of aircraft, with two different types of engines and completely different equipment, then it is obviously necessary to expand the Technical Division to cover the extra work engendered. But this certainly does not mean duplication of technical staff, provided that all overhaul and maintenance work is done at one base.

The actual size of a one-type fleet should have little or no bearing upon the numbers employed within the Technical Division—this will depend purely upon the degree of reliability and the degree of complication of the aircraft types operated.

Engineering work must be thorough if the highest degree of safety is to be obtained. Furthermore, if the Production Division is to reduce its labour costs to a minimum and at the same time is to reduce the time during which aircraft are under service, either in maintenance or overhaul, to a minimum, they will require thorough analysis work to be done by the Technical Division's engineers. *In fact, the lowest technical costs of operation require the same efficiency in technical engineering that is needed to obtain the highest degree of safety of operations.*

Technical standards are never static, but should always be changing as experience and specialist knowledge of the equipment is gained by actual operational experience.

All such changes will aim either at removing newly-seen risks in operation, or of increasing times between overhaul and maintenance checks, or of decreasing elapsed times to do the checks. Such changes must be based upon facts—and facts can only be established by careful analysis of results obtained from operations, overhaul and maintenance.

Thus, there is clearly the necessity for an effective two-way traffic in technical information within an airline, which can be explained in the diagram (*see* Fig. 5).

The technical instructions issued by the Technical Division should be limited to standards required, and should never reach into the productive methods to be used to reach those standards.

As a large proportion of the technical instructions that will be issued by the Technical Division will have to carry the approval of the local National Air Authority (such as the A.R.B. in Great Britain and the C.A.A. in the U.S.A.), it follows that the closest co-operation must exist between the Division and these Authorities, as well as with the Technical and Design Departments of the manufacturers.

Some operators today wisely limit all official contacts between themselves and the manufacturers on technical matters to their Technical Division and thus cut out all possibilities of confusion or divided authority.

No Technical Division can work in isolation. In fact, it is felt to be wise practice for the Technical Division's staff not to be centralised in a series of adjacent offices, but to be located in offices closely adjacent to their main source of evidence. Hence, for example, the engine engineer might be located in offices in the Engine Overhaul Shop, and the radio engineers in the Radio Repair Shop.

From this, it follows that all the overhaul and maintenance activities of an operator must be concentrated at one Base, where all sources of evidence can be close together and where interchange of information is simplified and investigations can be quickly and easily held.

The only exception, from an efficiency point of view, is that it is possible to undertake a few maintenance checks away from the main Base.

Any other split-up of technical facilities—especially overhaul—is likely to place a severe handicap upon the whole sequence of good airline overhaul and maintenance procedures and, in fact, must have a lowering effect upon both safety and economy.

The efficiency of an airline's Technical Division depends on their ability to establish quickly and accurately the facts of all incidents and irregularities and, secondly, their ability to formulate an effective preventive solution to all troubles that develop.

The effective employment of these simple methods leads to continued ability to decrease maintenance and overhaul effort, while maintaining or increasing safety and regularity of operations.

This work only ends on any one type of aircraft or equipment when that particular type of aircraft is sold and the Technical Division turns to a new type. If they are a skilled team, they will know exactly what they will try to avoid in a new type of aircraft and they will naturally influence their company to try and get a replacement aircraft which avoids as many as possible of the difficulties they have experienced on the old type. The value to an airline of a really first-class and efficient Technical Division cannot be over-emphasised.

14. Production Division

The realisation that the physical work of airline maintenance and overhaul is of a highly repetitive nature, and lends itself to the most modern production methods, is causing considerable changes to be made in airline engineering methods and organisation.

Airline engineering production work can be divided into two classes:—

(*a*) *Routine work*, that is, work the exact nature of which can be known in advance in exact detail.

(*b*) *Rectification work*, that is, work which depends upon an inspection process to establish the exact nature of what has to be done.

It is possible to do full "work preparation" in advance on all work of the first category.

An example is shown of "work preparation" applied to a power-plant change on a short-haul aircraft (*see* Fig. 6).

The first column of Fig. 6 shows the actual man-hours expended and elapsed time achieved by doing the power-plant change with little or no real and effective work preparation. The second column shows the result of work preparation, consisting of a method study, giving a sequence of operations, the supplying of equipment to enable the work team to do their work with the least physical effort and without leaving their

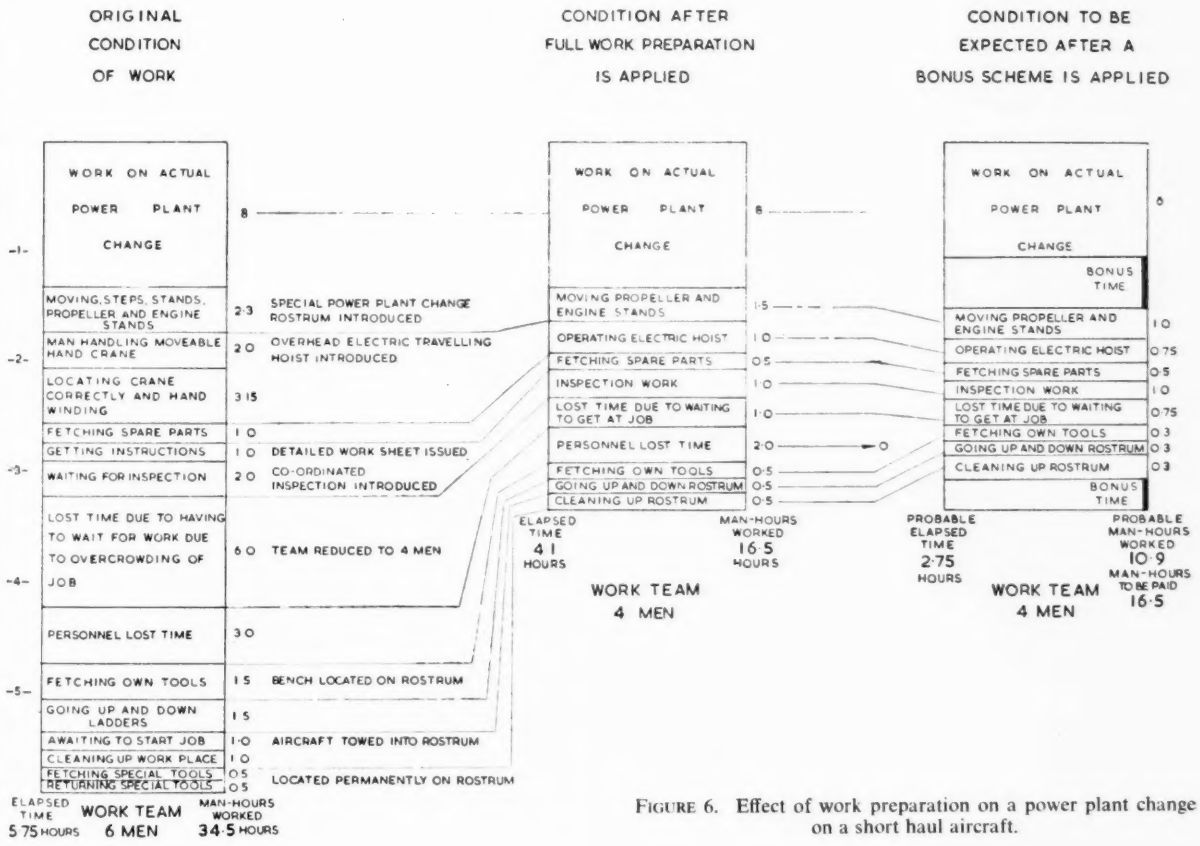

ORIGINAL CONDITION OF WORK
CONDITION AFTER FULL WORK PREPARATION IS APPLIED
CONDITION TO BE EXPECTED AFTER A BONUS SCHEME IS APPLIED
WORK ON ACTUAL POWER PLANT CHANGE
MOVING, STEPS, STANDS, PROPELLER AND ENGINE STANDS 2·3
MAN HANDLING MOVEABLE HAND CRANE 2·0
LOCATING CRANE CORRECTLY AND HAND WINDING 3·15
FETCHING SPARE PARTS 1·0
GETTING INSTRUCTIONS 1·0
WAITING FOR INSPECTION 2·0
LOST TIME DUE TO HAVING TO WAIT FOR WORK DUE TO OVERCROWDING OF JOB 6·0
PERSONNEL LOST TIME 3·0
FETCHING OWN TOOLS 1·5
GOING UP AND DOWN LADDERS 1·5
AWAITING TO START JOB 1·0
CLEANING UP WORK PLACE 1·0
FETCHING SPECIAL TOOLS 0·5
RETURNING SPECIAL TOOLS 0·5
SPECIAL POWER PLANT CHANGE ROSTRUM INTRODUCED
OVERHEAD ELECTRIC TRAVELLING HOIST INTRODUCED
DETAILED WORK SHEET ISSUED
CO-ORDINATED INSPECTION INTRODUCED
TEAM REDUCED TO 4 MEN
BENCH LOCATED ON ROSTRUM
AIRCRAFT TOWED INTO ROSTRUM
LOCATED PERMANENTLY ON ROSTRUM
ELAPSED TIME 5·75 HOURS
WORK TEAM 6 MEN
MAN-HOURS WORKED 34·5 HOURS
WORK ON ACTUAL POWER PLANT CHANGE
MOVING PROPELLER AND ENGINE STANDS 1·5
OPERATING ELECTRIC HOIST 1·0
FETCHING SPARE PARTS 0·5
INSPECTION WORK 1·0
LOST TIME DUE TO WAITING TO GET AT JOB 1·0
PERSONNEL LOST TIME 2·0
FETCHING OWN TOOLS 0·5
GOING UP AND DOWN ROSTRUM 0·5
CLEANING UP ROSTRUM 0·5
ELAPSED TIME 4·1 HOURS
MAN-HOURS WORKED 16·5 HOURS
WORK TEAM 4 MEN
WORK ON ACTUAL POWER PLANT CHANGE
BONUS TIME
MOVING PROPELLER AND ENGINE STANDS 1·0
OPERATING ELECTRIC HOIST 0·75
FETCHING SPARE PARTS 0·5
INSPECTION WORK 1·0
LOST TIME DUE TO WAITING TO GET AT JOB 0·75
FETCHING OWN TOOLS 0·3
GOING UP AND DOWN ROSTRUM 0·3
CLEANING UP ROSTRUM 0·3
BONUS TIME
PROBABLE ELAPSED TIME 2·75 HOURS
PROBABLE MAN-HOURS WORKED 10·9
MAN-HOURS TO BE PAID 16·5
WORK TEAM 4 MEN

FIGURE 6. Effect of work preparation on a power plant change on a short haul aircraft.

work place, and the introduction of a co-ordinated shop viewing under the direct control of the Production Division, full worker training, besides clearing up other minor details. The resulting drop in man-hours and elapsed time is a general indication of what can be expected, notably, a saving of 50 per cent. on direct labour and the reduction of elapsed time by nearly 25 per cent.

An improvement which is not shown and which is virtually inevitable, if work preparation is efficiently applied, is that the quality of the work will also improve—since correct work sequences, fully detailed instructions and correct tools, reduce the possibilities of human error and are vital to attain such reductions of effort.

By applying a bonus scheme to such a fully planned work sequence, a further reduction in elapsed time can be expected, although the direct labour cost of the job may remain the same as before.

This example does not indicate the end of possibilities of still further decreasing labour times and elapsed times. Refinements and improvements can, and should, be continuous.

It is therefore evident that the more work that can be converted from the second category of "rectification" (*i.e.* work the nature of which depends upon an inspection process) to "routine" work (*i.e.* work of which the full details are known before it is started), the more possible it is to reduce work time and work effort by careful work preparation.

This development has gone so far in certain companies that routine work (which includes modifications) now represents 85 per cent. of all physical work done, and only 15 per cent. is rectification work. The aim will be constantly to increase routine work until eventually it represents as nearly as possible 100 per cent. of all physical work.

15. Servicing Schedules

As in all repetitive production processes, it is necessary to keep the work load at an even rate throughout the year. Work loads are dependent upon traffic programmes, and these in turn produce seasonal peaks and troughs of activity. This is true for virtually every airline in the world in some form or other.

The main objectives before a Production Division are:—

(*a*) To meet exactly the technical standards laid down.

(*b*) To do the work necessary in the least possible elapsed time with the least possible man-hours.

(*c*) To assess future work accurately and be able to plan it out in order to maintain an even work load, year in and year out.

It has long been the practice to divide the work of servicing an airline's fleet into maintenance checks and overhauls.

16. Maintenance Checks

Maintenance checks are at present necessary for two reasons. Firstly, there are still certain items that require adjustment before that particular part is scheduled to undergo an overhaul. An obvious example is sparking plugs, which have not yet been developed to match engine overhaul life. They are therefore changed at pre-determined intervals during maintenance checks. This is a "routine" job. Secondly, there are still irregularities occurring in flight which may not affect the safety of the aircraft but which should be corrected

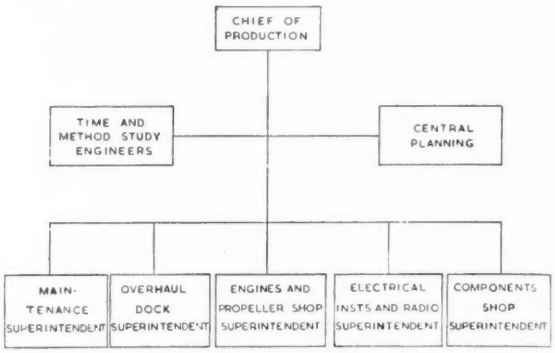


FIGURE 7. The production department.

during maintenance. An example is the failure of an instrument, the correction of which would be a "rectification" job.

In the first instance, which can be dealt with as "routine work," an airline can, by careful analysis of statistics and possible development work, push up the life between replacements of a non-lasting part to its technical limit, beyond which irregualr changes *increase* above the average rate considered acceptable.

Quite apart from the safety angle, it is obvious that it will be cheaper to do routine work than rectification work. Hence, true economy of effort becomes the real measure of the necessity of maintenance check work of a routine nature, and safety automatically follows.

In the second example, the frequency of irregular changes must, if they increase, call for thorough investigation. This is because irregularities in service invite added costs, not only in the Engineering Department, but also in Traffic and Operations. There is usually a large number of possibilities of causes of iregularities, ranging from incorrect operation of the equipment in the air, a faulty standard of overhaul, to faulty design or manufacture of the part in question.

Although in both the examples quoted, the Technical Division must initially accept responsibility, both for the irregularities themselves, as well as for establishing the true causes, the procedures, which should later be adopted to rectify the trouble cannot always be settled by the Technical Division alone, since work plans and work costs, and even possibly capital costs, may become involved. The Technical Division must decide on the new standard they require to reduce the incidence of irregularity. But the Production Department must be free to decide how best they can meet the new technical standard and technical changes necessary.

Thus, a steady development of maintenance

schedules can be seen as experience is gained of any one type of aircraft, firstly towards reducing the amount of rectification work and secondly towards the continued decline of total man-hours of work per aircraft flying hour available and thirdly, towards decreased elapsed time for each check.

17. Overhaul System

The proportion of maintenance work can be as low as 15 per cent. of all direct labour used on overhaul and maintenance. This percentage can, it is felt, be still further decreased.

Development in overhaul has aimed chiefly to reduce all work to a routine nature as far as possible, to plan and prepare the work in as great a degree as possible and so to divide the programme that Production Planning can keep direct labour work at a steady level throughout the year, regardless of traffic peaks.

Overhaul work is now normally carried out in a specially built dock. The work itself can be divided into three types of work:—

1. Recurrent overhaul, (*i.e.* routine overhaul and major maintenance work).
2. Scheduled overhauls.
3. Modification installation.

The overhauls themselves are checks, varying in flying service time between checks, according to the reliability of the aircraft type and the experience of the airline's Engineering Department. Currently, these checks on the more reliable long-haul types of transport aeroplanes fall due every 1,200 to 1,500 hours and there may be 8 to 12 such checks in a single cycle.

The " recurrent overhaul work " therefore, is all that work which may fall due at each overhaul check or each alternate overhaul check, and so on.

Scheduled overhauls are full overhauls of a major assembly generally achieved, if the standards of interchangeability will allow, by the complete removal of the assembly from the aircraft and its immediate replacement by a previously overhauled assembly.

As the proportion of " routine work " to " rectification work " on overhauls can be very high indeed, it follows that an accurate assessment of man-hours required can be obtained before the aircraft enters the dock.

Variations in planned man-hours in each overhaul required to meet traffic peaks and troughs are currently achieved in several different ways. It is already evident in well-organised airlines that a constant labour force can be fully employed the year round, regardless of traffic peaks, by scientific planning of all overhaul work.

18. Work Planning

Work planning, to be effective, must come under the Production Division and can be divided into Central Planning and Dispersed Planning.

The actual planning of the physical work, either in the maintenance hangar, overhaul dock or overhaul shops, can be decentralised. These decentralised planning groups will work to the basic plans prepared by the Central Planning Group. The Central Planning Group must be realistic in their basic planning and must always use the current measurements of technical efficiency as issued by the Technical Division specialist engineers.

19. Production Organisation

In Fig. 7 is shown the form of organisation which would meet the requirements of a modern Production Department.

Where the use of labour has been reduced to a low level, and the safety record is high, the form of organisation found is always of a direct nature. This is necessary in order to match responsibility with authority. Thus each supervisor responsible for one facet of production work is entirely responsible for all staff necessary to complete all work sequences within his Section.

This can lead to a shop organisation of the form shown in Fig. 8.

It should be noted that the control over spare parts should cover the setting of stock levels, stock recording and re-ordering procedures. On no account can production staff be held responsible for the rate of spare part consumption. This is the responsibility of the Technical Division, who set the standards required. It is these standards which set the rate of spare part consumption. Hence, the responsibility for the cost of

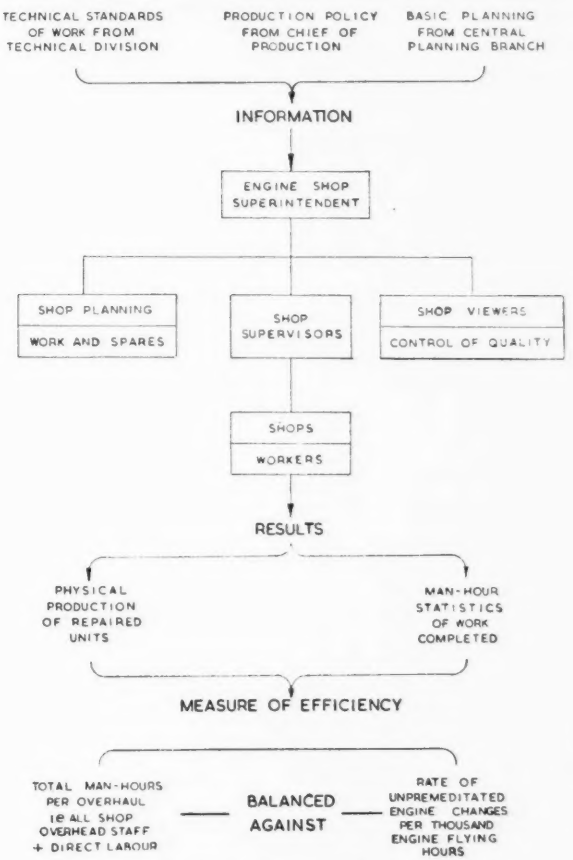


FIGURE 8. Shop organisation.

spares must be carried by the Technical Division and not by the Production Division. These spares costs must be constantly balanced by the Technical Division against the measures of technical efficiency already mentioned.

20. Inspection Department

It is a mandatory requirement of Civil Air Authorities that there should be a Chief Inspector, equipped with a separate Inspection Branch.

Under present developments, certain functions hitherto considered the responsibility of a separate Inspection Department are being progressively replaced by (*i*) the Technical Division, who are responsible for laying down all technical standards, and by (*ii*) shop viewers placed under the direct control of the shop superintendents in the Production Division.

The Inspection Department is therefore becoming an investigatory department, capable of checking any whole procedure to see that the standards laid down by the Technical Division are being consistently met by Production.

This development appears to be one of considerable importance, since experience already shows that it increases the real strength and ability of the Inspection Department to get the quality of work required. The reason for this is that the old inspection method often savoured of "police" action, whereas the new method places the Department in the position of offering the service of impartial and thorough investigation to both the Technical and Production Divisions.

Much further development lies ahead in this connection—and it seems possible that the separate Inspection Department will develop into a Quality Engineering Department.

PART IV
ENGINES

Where an Engineering Department has reached a reasonably high degree of efficiency, and the aircraft type operated a high degree of reliability, it will be found that engine costs become the major cost item of the Engineering Department. They may be responsible for possibly 50 per cent. - 75 per cent. of all the Engineering Department costs.

The reliability of the engine is also a considerable factor in the regularity of services.

There is today a large variation existing in approved overhaul times and especially in rates of irregularities that are returned by different companies operating even the same engine.

Increases of overhaul periods have to be agreed, not only by the engine manufacturer, but also by the local civil air authority. Reliability of past engine performance is the only criterion upon which the air authorities can base their decision to approve a requested increase of overhaul time.

Variations in engine overhaul times have a marked effect upon aircraft costs per hour flown. To a lesser degree, man-hours of direct labour per engine overhaul also affect these costs.

In Fig. 9, a graph is given of engine overhaul costs (direct labour, plus overhead engine overhaul staff, plus spare parts) for a modern piston engine fitted in a hypothetical large fleet of long-range aircraft operating at a utilisation rate of 2,400 hours per annum per aircraft.

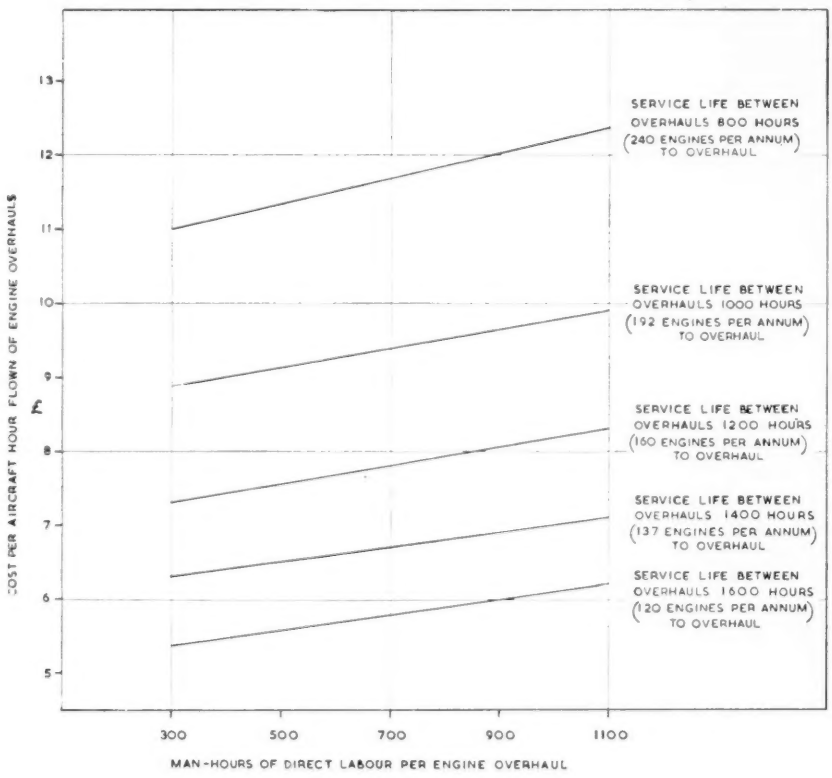

SERVICE LIFE BETWEEN OVERHAULS 800 HOURS (240 ENGINES PER ANNUM) TO OVERHAUL
SERVICE LIFE BETWEEN OVERHAULS 1000 HOURS (192 ENGINES PER ANNUM) TO OVERHAUL
SERVICE LIFE BETWEEN OVERHAULS 1200 HOURS (160 ENGINES PER ANNUM) TO OVERHAUL
SERVICE LIFE BETWEEN OVERHAULS 1400 HOURS (137 ENGINES PER ANNUM) TO OVERHAUL
SERVICE LIFE BETWEEN OVERHAULS 1600 HOURS (120 ENGINES PER ANNUM) TO OVERHAUL
COST PER AIRCRAFT HOUR FLOWN OF ENGINE OVERHAULS
£
13
12
11
10
9
8
7
6
5
300
500
700
900
1100
MAN-HOURS OF DIRECT LABOUR PER ENGINE OVERHAUL

FIGURE 9. Piston engine overhaul costs.

The curves represent costs per aircraft hour flown at varying engine service times from 800 hours to 1,600 hours, and for varying direct man-hours per overhaul from 300 to 1,100 hours.

Figure 10 shows some typical engine service life growths in service for different engines by different operators.

The importance of increasing the engine service hours between overhaul is self-evident for economic reasons.

Figure 11 shows the influence of different rates of unpremeditated engine changes on engine overhaul costs and hence on aircraft costs. Here can be seen quite clearly the fact that reliability and economy are synonomous, or, conversely, that engine unreliability is one of the most expensive luxuries in air transport.

Approved service lives of engines between overhaul now reach up to 1,500 - 1,600 hours, and reliability runs at around 0·3 - 0·2 unpremeditated engine changes per 1,000 engine hours.

Irregular engine change rates also have an effect upon the number of spare engines that must be held against installed engines.

It has been found that, where engines are overhauled by the operator, as is the case in the majority of the world's major airline companies, the rates of irregular engine changes and of technical late departures and malfunctions are lower than where engine overhauls are sub-contracted out. This can be attributed to the fact that the whole of the technical knowledge and data to be gained from the methods of operating the engines in the air, through to the detailed data of overhaul, is in the hands of the operator's Technical Division. A competent engine team is going to look at these different phases as directly linked up with each other and wih pay closer attention to all the details which will give a high degree of regularity of engine operation than if part of their responsibility is shared with a sub-contractor, over whom they have little or no control.

An important development which is having to be given increasing attention is the repair and salvage of engine spare parts. If reference is made to Fig. 10 and a point is taken on the 1,200 hour service life curve at a

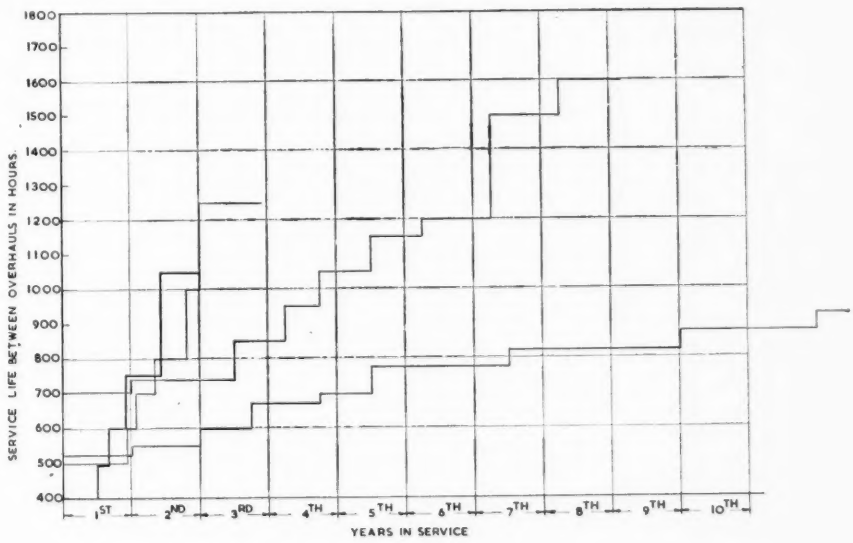


FIGURE 10. Typical service life growth of engine.

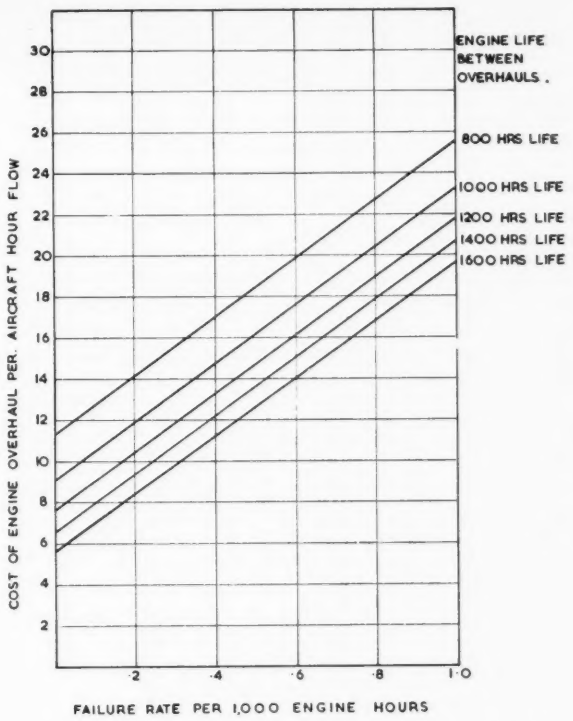


FIGURE 11. Influence of engine failures on overhaul costs.

labour figure of 900 man-hours, it is found that the break-up of costs at this point would be:—

	% of cost per engine-hour flown
Direct Labour	10·0
Engine Overhaul Overhead Staff ..	10·0
Spare Parts	80·0
	100%

Engine spare parts consumption is dependent firstly

on the tolerances and service lives laid down by the engine manufacturer. These are based on his design and development experience. The changing or development of these tolerances, which will tend to ease the rate of spare part consumption, depends upon operational experience and the manufacturer is somewhat reluctant to widen his tolerances and lives, unless he is given factual evidence by the operator to justify such changes. Thus the impulse to change such standards must come from the operator first. As the operator himself wants to increase his service hours between overhauls, and for this purpose is constantly seeking greater reliability upon which to base his demands for higher engine service life, his technical engineers are more interested in maintaining the engine standards which have already given reliability, than studying the possibility of changing those standards to cut engine spares consumption.

This is understandable, since the consumption rate of spares per overhaul does not greatly vary with increased service life, and hence the increasing of engine service life is one way of decreasing engine spares costs per engine or aircraft flying hour.

On the engine manufacturer's side, there does not, in the past, seem to have been any notable enthusiasm towards suggestions which would increase the life of specific parts of the engine. Those airlines which are alive to the situation are taking an even closer look at their spare parts consumption rates, and money spent on developing acceptable salvage and repair schemes invariably shows big profits in reduced spares consumption rates. This development is likely to increase.

21. Other Airborne Equipment

No other single item of a transport aircraft accounts for such a high percentage of engineering costs as do the engines. Yet the same technique applied to overhauling all equipment will repay the operator.

22. Utilisation Rates

By utilisation rate is meant the average hours per day per aircraft that a fleet is actually flying and earning revenue.

An example of the effect of utilisation rates on the engineering costs of a medium fleet of long-range aircraft is shown in Fig. 12. The curve becomes even steeper if it is drawn up for total costs per aircraft hour, since there would be added all other non-engineering overhead costs. The highest possible utilisation is an absolute necessity for the most economic results.

Utilisation rates are affected by five main influences:—

(*i*) Traffic and Sales Planning.
(*ii*) Skill of operator's Engineering Department.
(*iii*) Overhaul and Maintenance System in use.
(*iv*) Type of aircraft used.
(*v*) Size of fleet.

(*i*) *Traffic and Sales Planning* lies outside the control of the Chief Engineer, yet the actual planning of the use of the aircraft is of vital importance to the

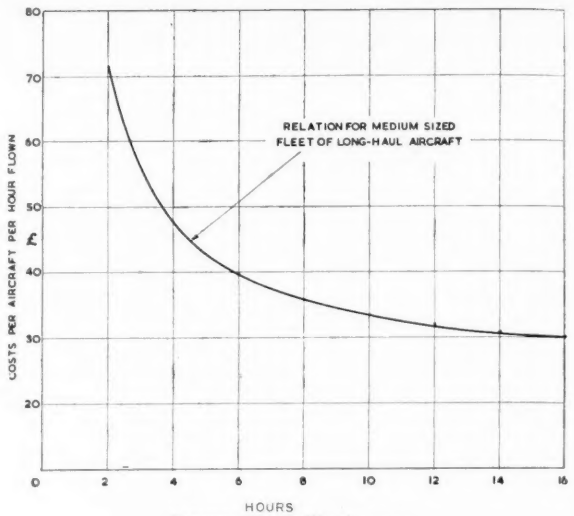


FIGURE 12. Utilisation rate.
Average aircraft hours flown per whole fleet per day aircraft.

Engineering Department. The traffic planners need the maximum potential time available within every 24 hours for each aircraft, and this in turn demands that the elapsed time to do maintenance checks shall be kept to a minimum by the Engineering Department. As regularity of service is of considerable importance, traffic planners will take cognisance of the previous record of elapsed times taken by Engineering for maintenance checks, as well as regularity rates, and these will influence their traffic plan. At the same time, they must allow the Engineering Department adequate time to carry out maintenance and overhaul. It is most unlikely that the old practice of having one or more standby aircraft, serviceable and in reserve at the main base, will be tolerated in the future.

(*ii*) *The skill of the Engineering Department* as a whole has a large bearing upon utilisation—particularly in its ability to keep down its elapsed times to do maintenance and overhaul checks and its rates of irregularities. When rates of irregularities are high, aircraft utilisation rates will be low.

(*iii*) *The Overhaul and Maintenance System in use* has a very large bearing upon utilisation rates. Any system used is built up of a number of checks, and these will determine the amount of off-service time of the fleet. Present-day overhaul and maintenance systems vary widely, especially in the amount of elapsed time to undertake checks.

(*iv*) *The type of aircraft used* has been found by experience to have a large bearing upon utilisation. Firstly, if a fleet is in an undeveloped stage, it will be liable to develop serious troubles which may preclude the development of a really short elapsed time schedule of overhaul and maintenance to be adopted.

The same handicap can be experienced by lack of adequate interchangeability, not only of assemblies but of detail parts. Secondly, if major jobs of re-work arise which require long elapsed times to complete, then no consistently speedy system of overhaul and maintenance

is possible—and a low aircraft utilisation rate will develop—in spite of all the efforts of the airline's Engineering Department.

(*v*) *Size of fleet* has a bearing upon utilisation rates, insofar as it determines the form of the maintenance and overhaul systems and organisation. Maximum efficiency is obviously gained when the size of the fleet *and* the utilisation rate are such that an overhaul team can be kept occupied at a steady pace throughout the year. Where a fleet is too small to justify a continuously-employed airframe overhaul team, it is no less essential to employ a progressive or scheduled overhaul system.

Utilisation rates, therefore, are by no means wholly dependent upon the Engineering Department. Put in a simple form, it seems vital that the Engineering Department should continuously strive to drive down the elapsed times for all maintenance and overhaul checks to a minimum, in order to give Traffic Planning the possibility of taking up excess serviceable time in whatever manner is open to them, or selling excess aircraft.

23. Airframe Selection

The matching of aircraft to route patterns has been much discussed, yet relatively few different types of aircraft are in fact made to do the bulk of the world's air transport business—in most instances with economic success, although obviously without being ideally matched to suit all the different route patterns. Apart from the necessity of close performance studies of any new aircraft likely to be suitable to an operator, it is evident that, in future, reductions of operating costs can be made by more attention being paid to the vital engineering aspects of the aircraft.

Nothing can damage an operator's financial position so quickly or so drastically as the grounding for technical reasons of the type of aircraft with which he has chosen to equip himself.

Airline managements will undoubtely have to insist that their Engineering Departments will take all possible action to assure themselves that no such grounding action is likely to occur to any type which they recommend for purchase.

Efficient operators will go far beyond this and will no doubt insist that no new aircraft be purchased which is seen to embody causes of recognised troubles experienced on previous types. Nor is any operator likely to view with much favour a new untried type of aircraft, unless traffic competition compels him to invest in such an aircraft and unless he has considerable confidence in the ability of his own engineering team.

It appears abvious that the proportion of potential traffic and financial benefit which an operator will gain by introducing either a revolutionary new aicraft type, or a type fundamentally in advance of the type he is already operating, will depend directly on the efficiency of his Engineering Department.

24. Fuel Consumption

There is at present, with a few exceptions of a rudimentary nature, no effective control put upon the consumption of fuel by operators. As fuel can absorb between 16 per cent. and 19 per cent. of total costs (*see* Fig. 2), it is obviously a matter which requires urgent attention.

It can be said that at the present time most of the world's operators have no effective means of controlling fuel consumption, and very few indeed have any idea of the potential economy that could be reaped by effective control. The methods of control cover three separate processes. Firstly, more intensive work will have to be put into the development and laying down of engine operational techniques. Secondly, it will be necessary to record economically, accurately and continuously, all flight conditions having a bearing upon engine operation. In other words, continuous flight recording of all atmospheric data, engine data and aircraft data will be required. Thirdly, it will be necessary to devise a method of monitoring the records of flights, so that corrective action can be taken. It seems, however, that a degree of automaticity will eventually have to be introduced, so that the best economic conditions can always be maintained for engine operation and so cut down the monitoring after the event.

Even today, it is seen that the potential economy is considerable, and it is not likely that the present unbusinesslike methods will be allowed to continue much longer.

Conclusion

There seems little doubt that, at the present time, there is scope for effecting considerable economies in the operating costs of airlines.

Where such economies are achieved and are based on sound technical principles, it can be expected that safety and regularity of operations will also increase. In fact, safety and economy are virtually linked together; the greater the degree of technical inefficiency, the greater the likelihood of accidents and irregularities, and *vice versa.*

The changes in the efficiency of an airline's Engineering Department can be assessed by balancing technical costs and human effort figures against the various rates of irregularities.

Continual increase of engineering efficiency is vital to enable an operator to absorb new types of aircraft efficiently and economically and thus to be in a position to extract the maximum financial benefit from them.

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STATISTICAL APPENDIX

It is perhaps useful to put in proper perspective the present air transport business of the world.

In 1953, the world's scheduled airlines produced 3,720-million short ton miles of revenue-paying load. This was split up as shown in Table I.

TABLE I

	Short ton miles in millions	*Per cent. of World total*
United States Airlines	2118·4	56·9
United Kingdom Airlines	195·3	5·25
Rest of world, excluding Soviet Russia and Satellites	1406·3	37·85
World Total.	3720·0	100·0

Source—I.A.T.A.

The degree of safety reached can be seen by reference to Tables II and III.

The average number of fatalities per 100,000,000 passenger-miles for the United States and the United Kingdom carriers for the six years 1949 to 1954 inclusive were as follows:—

	Fatalities/ 100,000,000 Passenger-miles
U.S. Carriers	0·7
U.K. Carriers	3·6

Most aircraft at present used by civil air transport companies are predominantly American, as can be seen by an analysis of the fleets of the 68 operators who are members of I.A.T.A., as at 31st December, 1953:—

Total aircraft operated	2441	100%
American-built aircraft	2054	84%
U.K.-built	292	12%
Other aircraft	95	4%

Source—I.A.T.A.

It has been felt necessary to present these figures to show the predominant position the American operators have reached, both in safety of operations and the capacity of their business. It is only right here to recognise that much of the advance thinking of airline technical organisation and methods of procedure have come from American airline companies over the past ten years—to whom due credit should be given.

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TABLE II

Year	*Revenue passenger miles* × 1,000			*Passenger fatalities*			*Fatality rate per 100,000,000 passenger-miles all British scheduled services*
	British Corporations	*British independent operators of scheduled services*	*Total*	*British Corporations*	*British independent operators of scheduled services*	*Total*	
1949	607,000	7,500	614,500	43	0	43	7·0
1950	784,000	10,200	794,200	49	0	49	6·2
1951	1,054,000	12,300	1,066,300	0	0	0	—
1952	1,207,000	26,600	1,233,600	0	0	0	—
1953	1,379,000	52,500	1,431,500	61	0	61	4·3
1954	1,431,000*	93,800*	1,524,800*	84	0	84	5·5
			6,664,900			237	

*Provisional.

Source—Ministry of Transport and Civil Aviation, London.

TABLE III

Year	*Revenue passenger miles* × 1,000			*Passenger fatalities*			*Fatality rate per 100,000,000 passenger-miles all American scheduled services*
	U.S. International	*U.S. Domestic*	*Total*	*U.S. International*	*U.S. Domestic*	*Total*	
1949	2,053,980	6,744,425	8,798,405	0	93	93	1·1
1950	2,206,396	8,012,536	10,218,932	48	96	144	1·4
1951	2,599,915	10,566,169	13,166,084	31	142	173	1·3
1952	3,019,810	12,528,437	15,548,247	94	46	140	0·9
1953	3,367,576	14,691,217	18,058,793	2	86	88	0·5
1954	3,816,000	16,706,000	20,522,000	0	16	16	0·08
			86,312,461			654	

Source—Air Transport Association of America, Washington, D.C.

The Solution of Aeroelastic Problems on Wings of Arbitrary Plan Form by Matrix Methods

by

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(Short Brothers and Harland Ltd.)

SUMMARY: It has been adequately demonstrated that the reduction of structural and aeroelastic problems to a form suitable for computation is best done using a matrix formulation. The present paper outlines such a formulation of the aeroelastic problems on wings of arbitrary plan form and gives a method of solution which has been found satisfactory over a wide range of practical calculation. In the symmetric case the problem of manoeuvre margin due to aeroelastic effect is considered and in the anti-symmetric case the rolling effectiveness and the reversal speed for aileron controls are dealt with.

1. Introduction

The estimation of aeroelastic effects on aircraft can normally be carried out by a straightforward iteration process, but such a process demands continual supervision by a person with a knowledge of the physical implications of the iteration. The present paper is an attempt to reduce the aeroelastic problem on a swept wing to a fixed routine of sufficient definition to enable a computor to bring the work to a numerical conclusion. This problem, in common with most characteristic value problems, lends itself to matrix formulation and solution, and only an elementary knowledge of matrix technique is necessary to follow the method and obtain a numerical result.

To specify this problem the aerodynamic load on any section of the wing due to an arbitrary distribution of wash-out must be known and also the structural distortion caused by this load at each section along the wing. Both of these properties are expressed in the form of matrices of influence coefficients and are described in Sections 2 and 3. It will be noted that the span is subdivided angularly, rather than linearly, to get a concentration of points at the critical position (*i.e.* the wing tip); thus, lifting plane methods such as that of Falkner are not immediately suitable.

In the symmetric case the method yields the loading on a deformable wing under any condition and thus the change in manoeuvre margin due to aeroelastic effects. In the anti-symmetric case the wing loading can be obtained and hence the steady rate of roll and aileron reversal speed.

The main limiting assumption of the analysis is that the wing is considered to be rigid in the chordwise direction or, in other words, that aeroelastic effects do not produce camber changes. This assumption is valid for the higher aspect ratios but is open to some doubt in the case of a delta plan form. The method presented here, however, may be generalised to include chordwise distortion and this subject will be considered in more detail at a later date.

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Notation

$[B]$	square matrix relating γ and α
$\{\gamma\}=\Gamma/(bV)$	non-dimensional vortex distribution column matrix
$\{\alpha\}$	incidence distribution column matrix
$\{L_i\}$	load on spanwise increments Δy_i, column matrix
b	wing span
q	dynamic pressure $\frac{1}{2}\rho V^2$
y_i	spanwise position
m	number of divisions in semi-span
V	velocity of air relative to wing
$[A]=[B]\{\Delta y_i\}^{-1}$	
$[A]^{-1}$	square matrix of aerodynamic influence coefficients
$[\theta_L]$	square matrix of bending influence coefficients
$[d]$	diagonal matrix of distances from Q_0 line to aerodynamic centre, positive when measured forward from Q_0
Q_0	locus of points defined in Section 3
$[\theta_T]$	square matrix of torsional influence coefficients
$[S]$	*see* equation (4)
$[C]$	matrix similar to $[S]$ where $[d]$ is replaced by distances from aileron c.p. to Q_0 line
$\{L_{SR}\}$	rigid wing loading
$\{\Delta L_{Si}\}$	incremental loading due to deformation
$\{L_{p_1}\}$	loading due to unit $pb/(2V)$
$pb/(2V)$	non-dimensional rate of roll of elastic wing
$\{pb/(2V)\}_R$	non-dimensional rate of roll of rigid wing

2. Aerodynamic Influence Coefficients

Many methods are available for the estimation of aerodynamic loads on arbitrary plan forms from the simple assumptions of strip loading to the complicated lifting surface theories of Falkner and Multhopp. The degree of accuracy required must play a large part in the determination of the method to be used, but it must also be remembered that component accuracy is not always reflected to a worthwhile degree in the final answer.

For straight wings, a simple strip theory approach

gave sufficient accuracy in the estimation of aerodynamic loading. With the introduction of sweep, however, it becomes necessary to allow for a modification in the form of loading and the induction effects are aggravated to such an extent that it can no longer be assumed that the local lift slope is independent of the incidence distribution. The effect of sweep on centre of pressure has also assumed some importance, especially on wings designed on the aero-isoclinic principle, so that the choice of method is now confined to the lifting surface theories or, alternatively, Küchemann's[1] modified lifting line theory in which he makes an empirical correction for centre of pressure position. In general it is considered that the assumptions of this latter method are compatible with the overall accuracy requirement of the calculation and it is thus recommended for use.

The method is based on Multhopp's approach to the problem of determination of aerodynamic loading on straight wings, with an empirical correction to take account of sweep and its effect on centre of pressure position. The wing is divided into three working sections:—

(*i*) The centre section of a swept wing, assuming infinite aspect ratio.
(*ii*) Sheared wing.
(*iii*) Tip section which is regarded as part of the centre section of a swept forward wing.

Assuming a special chordwise distribution we can obtain the result

$$a_C = a_0\left(1-\phi\Big/\frac{\pi}{2}\right)$$
$$a_S = a_0(\cos\phi)$$
$$a_T = a_0\left(1+\phi\Big/\frac{\pi}{2}\right)$$

where a_C, a_S, a_T are the local lift slopes at centre, sheared and tip sections respectively, a_0 is the local lift slope of the two-dimensional aerofoil and ϕ is the angle of sweep at each section. The movement of the aerodynamic centre from the quarter point is then

$$\frac{\Delta h_C}{C} = \phi/(2\pi)$$
$$\frac{\Delta h_S}{C} = 0$$
$$\frac{\Delta h_T}{C} = -\phi/(2\pi)$$

and the form of the transition is determined from an empirical curve due to Küchemann[1].

Using these modifications to lifting line theory and applying certain other minor corrections to the fundamental Multhopp approach, we finish up with a loading matrix of the form

$$[B]\{\gamma\} = \{\alpha\}. \quad . \quad . \quad . \quad . \quad (1)$$

Now consider the lift on a spanwise increment given in terms of the circulation (Fig. 1)

$$L_i = 2bq\Delta y_i\gamma_i. \quad . \quad . \quad . \quad (2)$$

As $$y_i = \frac{b}{2}\cos\frac{\pi i}{2m}$$

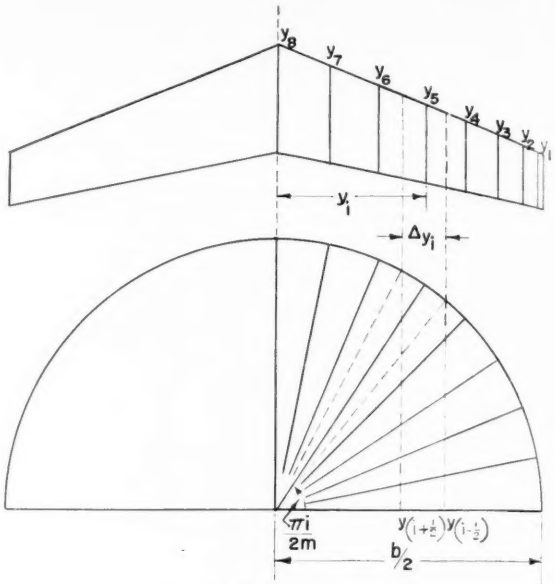

FIGURE 1.

where m is the number of divisions along the semi-span and the lengths Δy_i are given as follows

$$\Delta y_i = y_{(i-\frac{1}{2})} - y_{(i+\frac{1}{2})} = \frac{b}{2}\left[\cos\frac{\pi(i-\frac{1}{2})}{2m} - \cos\frac{\pi(i+\frac{1}{2})}{2m}\right]$$
$$= \frac{b}{2}\left[2\sin\frac{\pi i}{2m}\sin\frac{\pi}{4m}\right] \simeq \frac{b\pi}{4m}\sin\frac{\pi i}{2m},$$

with the exception of the last section where half the increment Δy_m is used and is given as follows

$$\Delta y_m = \frac{b\pi}{8m}\sin\frac{\pi i}{2m}.$$

Now substituting in equations (1) and (2) we have

$$\{L_i\} = 2bq[\Delta y_i][B]^{-1}\{\alpha_i\}$$

where $[\Delta y_i]$ is a diagonal matrix, or,

$$[B][\Delta y_i]^{-1}\{L_i\} = 2bq\{\alpha_i\}.$$

Now if we put $[B][\Delta y_i]^{-1} = [A]$

it will be found that the matrix $[A]$ is symmetric, thus simplifying considerably the task of inversion. Hence

$$\{L\} = 2bq[A]^{-1}\{\alpha\}.$$

The matrix $[A]^{-1}$ may now be looked upon as a matrix of aerodynamic influence coefficients.

It is also apparent that due to induction effects there will be a difference between the aerodynamic loading matrix for symmetric and anti-symmetric incidence distributions, thus

$$\{L_s\} = 2bq[A_s]^{-1}\{\alpha_s\} \quad . \quad . \quad (3)$$
$$\{L_a\} = 2bq[A_a]^{-1}\{\alpha_a\} \quad . \quad . \quad (4)$$

3. Structural Influence Coefficients*

Consider a wing as shown in Fig. 2. Suppose that a load is applied at varying points along AB, then it is possible to determine experimentally, or by calculation, the point at which no rotation of the section AB will

*The method employed here is identically that due to Broadbent[2].

take place. If this point is determined for a number of sections the locus of these points is known as the Q_0 line and bears some resemblance to the flexural axis on a straight wing.

Now if a load is applied at any point on the wing it can be looked upon as a load on the Q_0 line and a torque about it; we shall deal with the two parts separately.

Suppose a unit load is placed on the Q_0 line at any given section and the rotation of each section due to this load is measured or calculated. By loading each section in turn, a matrix can be produced which will give the rotation of each section under any known loading on the Q_0 line, assuming that the distributed load can be considered as a number of concentrated loads, one being applied at each strip. Thus we write

$$[\theta_L]\{L\} = \{\alpha_L\}.$$

The torque about the Q_0 line is treated in a similar fashion. A unit torque is applied at each section and a matrix produced, as before, of the influence of this at each other section. The torque is given by the column

$$[d]\{L\}$$

where $[d]$ is a diagonal matrix having as its elements the distance between the Q_0 line and the aerodynamic loading locus. Thus we write

$$[\theta_T][d]\{L\} = \{\alpha_T\},$$

and combining both contributions we have

$$[\theta_L]\{L\} + [\theta_T][d]\{L\} = \{\alpha_L\} + \{\alpha_T\} = \{\alpha\}.$$

Assuming that the position of the aerodynamic axis is known and thus $[d]$, this equation can be written

$$[S]\{L\} = \{\alpha\} \quad . \quad . \quad . \quad (5)$$

where $[S] = [\theta_L] + [\theta_T][d]$.

In Section 5, however, aileron loads are dealt with which are not on the same centre of pressure as the normal wing loads, thus the matrix $[S]$ is now modified and we have

$$[C]\{L\} = \{\alpha\} \quad . \quad . \quad . \quad (6)$$

where $[C]$ applies to control loads.

4. The Symmetric Case

According to equation (3) the lift in the symmetric case may be expressed in terms of the incidence as

$$\{L_s\} = 2bq[A_s]^{-1}\{\alpha_s\}.$$

Now the incidence may be written

$$\alpha_s = \alpha_0 + \alpha_b + \alpha_d$$

where α_0 = basic incidence
α_b = built-in twist,
α_d = twist due to structural elasticity.

Thus substituting in equation (3) we get

$$\{L_s\} = 2bq[A_s]^{-1}\{\alpha_0 + \alpha_b\} + 2bq[A_s]^{-1}\{\alpha_d\}^*.$$

According to Section 3 the structural deformation may be expressed in the form

$\{\alpha_d\} = [S]\{L_s\}$, and thus

$$\{L_s\} = 2bq[A_s]^{-1}\{\alpha_0 + \alpha_b\} + 2bq[A_s]^{-1}[S]\{L_s\}. \quad (7)$$

*The effect of wing inertia may be incorporated in this equation if necessary.

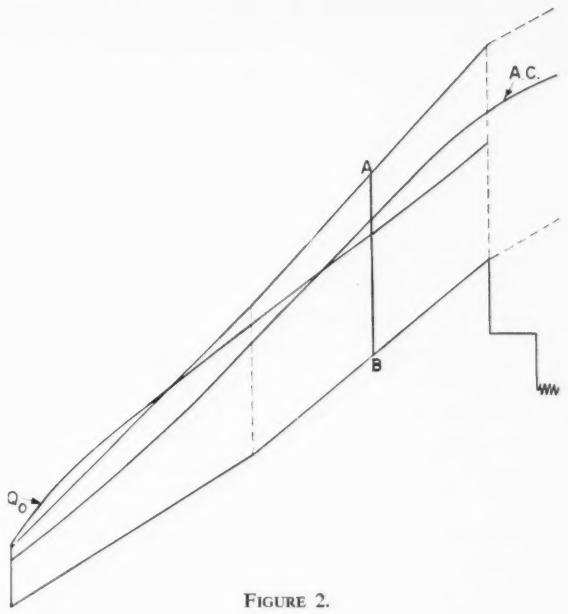

FIGURE 2.

This equation now provides us with a matrix relationship by which the column vector $\{L_s\}$ can be obtained by iteration or any other suitable method.

As a first approximation assume that the structural deformation is zero, thus giving the rigid wing loading

$$\{L_{sR}\} = 2bq[A_s]^{-1}\{\alpha_0 + \alpha_b\}.$$

Then the first increment in deformable load will be given by

$$\{\Delta L_{s1}\} = 2bq[A_s]^{-1}[S]\{L_{sR}\}.$$

This increment will in turn give rise to the load

$$\{\Delta L_{s2}\} = 2bq[A_s]^{-1}[S]\{\Delta L_{s1}\}$$

and so on, provided that the series is convergent, until a point is reached when all subsequent increments can be neglected, thus

$$\{L_s\} = \{L_{sR}\} + \{\Delta L_{s1}\} + \{\Delta L_{s2}\} + \ldots.$$

However, after a certain small number of iterations the dominant latent root will emerge, giving

$$\{\Delta L_{s,K+1}\} = 2bq\lambda\{\Delta L_{sK}\},$$

and thus we are merely faced with the problem of summing a geometric series to infinity given as follows

$$\{L_s\} = \{L_{sR}\} + \{\Delta L_{s1}\} + \ldots. + \frac{1}{1-2bq\lambda}\{\Delta L_{sK}\}. \quad (8)$$

In practice it will be found that for tolerable structural deformations, the latent root to a sufficient degree of accuracy will emerge after two or three iterations.

Thus the loading on the deformable wing $\{L_s\}$ may be compared with that of the rigid wing $\{L_R\}$ and hence, the movement of centre of pressure due to aeroelastic effects may be determined. It will be observed that in the case of a loading gain due to wing deformation the divergence speed of the wing can be immediately obtained as the value of q which makes $1-2bq\lambda=0$.

5. The Anti-symmetric Case

For the anti-symmetric case, equation (2), the lift may be expressed in terms of incidence as for equation (4)

$$\{L_a\} = 2bq\,[A_a]^{-1}\,\{\alpha_a\}$$

where the incidence is now given as follows

$$\alpha_a = \alpha_A + \alpha_p + \alpha_d$$

and α_A is the effective wing incidence which gives a lift distribution equivalent to that of a given aileron deflection, α_p is the incidence increment due to rate of roll and α_d is the twist due to structural elasticity.

Following the symmetric case we may write

$$\{L_a\} = 2bq\,[A_a]^{-1}\,\{\alpha_a + \alpha_p\} + 2bq\,[A_a]^{-1}\,\{\alpha_d\}. \quad (9)$$

However, α_d is in this case made up of a part based fundamentally on aileron loading and a part based on wing loading; thus by analogy with Section 4 we see that

$$\{\alpha_d\} = [C]\,\{L_{AR}\} + [S]\,\{\Delta L_A\} + [S]\,\{L_p\},$$

where $\{L_a\} = \{L_{AR}\} + \{\Delta L_A\} + \{L_p\}$.

Substituting in equation (9) we get

$$\{L_a\} = 2bq\,[A_a]^{-1}\,\{\alpha_A + \alpha_p\} + \\ + 2bq\,[A_a]^{-1}\left\{[C]\,\{L_{AR}\} + [S]\,\{\Delta L_A\} + [S]\,\{L_p\}\right\} \quad (10)$$

From this equation the main anti-symmetric cases of interest, namely steady rate of roll and aileron reversal speed, may be obtained.

STEADY RATE OF ROLL

Under conditions of steady rate of roll the rolling moment will be zero, thus

$$[y_i]\,\{L_a\} = 0$$

or, splitting up into a part due to aileron loading and a part due to rolling we get

$$[y_i]\left\{\{L_A\} + \{L_p\}\right\} = 0$$

where $\{L_A\} = \{L_{AR}\} + \{\Delta L_A\}$

and

$$\{L_A\} = 2bq\,[A_a]^{-1}\,\{\alpha_A\} + \\ + 2bq\,[A_a]^{-1}\left\{[C]\,\{L_{AR}\} + [S]\,\{\Delta L_A\}\right\}. \quad (11)$$

Thus for any given dynamic pressure, $\{L_A\}$ may be found in exactly the same fashion as in the symmetric case.

Now if $\{L_{p1}\}$ is the loading due to unit rate of roll,

$$\{L_{p1}\} = 2bq\,[A_a]^{-1}\,\{\alpha_{p1}\} + 2bq\,[A_a]^{-1}\,[S]\,\{L_{p1}\}, \quad (12)$$

where $\{\alpha_{p1}\}$ is the incidence due to unit rate of roll and $\{L_{p1}\}$ can be obtained by the usual iteration process. The actual rate of roll $pb/(2V)$ may be obtained from

$$[y_i]\left\{\{L_a\} + \{L_{p1}\}\frac{pb}{2V}\right\} = 0. \quad (13)$$

AILERON REVERSAL SPEED

Under conditions of exact aileron reversal there is no rate of roll. Thus $\alpha_p = 0$ and equation (10) becomes

$$\{L_a\} = 2bq\,[A_a]^{-1}\,\{\alpha_a\} + \\ + 2bq\,[A_a]^{-1}\,[C]\,\{L_{AR}\} + [S]\,\{\Delta L_A\}\Big\}. \quad (14)$$

In this case, however, we are looking for q, the dynamic pressure at which aileron reversal will occur or, in other words, the value q for which the equation

$$[y_i]\,\{L_a\} = 0. \quad (15)$$

As in the symmetric case we solve by successive iteration, thus

$$\{L_{AR}\} = 2bq\,[A_a]^{-1}\,\{\alpha_a\}$$
$$\{\Delta L_{A1}\} = 2bq\,[A_a]^{-1}\,[C]\,\{L_{AR}\}$$
$$\{\Delta L_{A2}\} = 2bq\,[A_a]^{-1}\,[S]\,\{\Delta L_{A1}\}$$
$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$$
$$\{\Delta L_{AK}\} = 2bq\,[A_a]^{-1}\,[S]\,\{\Delta L_{A,K-1}\}.$$

As before, after a certain small number of iterations the dominant latent root will appear, thus

$$\{\Delta L_{A,K+1}\} = 2bq\lambda\,\{\Delta L_{AK}\}.$$

Substituting in equation (15) we obtain

$$k_1 q + k_2 q^2 + k_3 q^3 + \ldots\ldots \frac{k_k q^k}{1 - 2bq\lambda} = 0 \quad (16)$$

where

$$k_1 = 2b\,[y_i]\,[A_a]^{-1}\,\{\alpha_a\}$$
$$k_2 = 4b^2\,[y_i]\,[A_a]^{-1}\,[C]\,[A_a]^{-1}\,\{\alpha_a\}$$
$$k_3 = 6b^3\,[y_i]\,[A_a]^{-1}\,[S]\,[A_a]^{-1}\,[C][A_a]^{-1}\,\{\alpha_a\}$$

and so on.

This polynomial is found in general to be of the fourth or fifth order and can easily be solved for a real root by numerical methods giving q the reversal dynamic pressure.

Conclusion

The problem of aeroelastic distortion on wings of arbitrary plan form has been formulated and methods of solution presented which have proved satisfactory from the point of view of manual computation. However, solutions of aeroelastic problems now tend to be left to digital computing machinery and for this purpose only the formulation is required, the solution being left to the normal subroutines of the machinery. On low aspect ratio plan forms chordwise distortion is now of some significance and a generalisation of this method to cover this point will be dealt with at a later date.

ACKNOWLEDGMENTS

The authors wish to thank Mr. D. Keith-Lucas, Director and Chief Designer, Short Bros. and Harland for permission to publish this paper, and Professor A. R. Collar for pointing out some errors in the original paper.

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TECHNICAL NOTES

Contributions to this Section of the JOURNAL *will be eligible for Journal Premium Awards and will normally be published within two months of being received.*

Note on the Accuracy of Supersonic Tunnels

by

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THE effort required to produce very accurate supersonic nozzles has suggested the need[1] for criteria from which the order of accuracy required for quantitative experiments can be deduced. The purpose of this note is to indicate a way of obtaining such criteria for measurements of aerodynamic forces, but also to point out that "sufficiently accurate" nozzles for such measurements are indeed very difficult to produce and to suggest that a remedy might first be sought in interference corrections.

The reason for the exacting demand on accuracy lies in the fact that practically useful bodies must be relatively thin or slender. The percentage error in a force measurement is proportional to the ratio of the "background" flow perturbation in the working-section to the perturbation generated by the body, and if the body is thin or slender, this ratio remains significant even if the background perturbation is very weak. This may be seen more clearly by considering a simple example.

Suppose the drag of an aerofoil in two-dimensional, supersonic flow is to be measured by a pressure traverse downstream. On inviscid theory, a rough approximation for the drag coefficient is

$$C_D \propto \int p'^2 dy, \qquad p' = (p - p_1)/p_1,$$

where p_1 and p denote respectively the pressure in the undisturbed stream and the local pressure on the traverse line crossing the wake from nose-shock to nose-shock. Let ϕ_a and ϕ_b denote the respective perturbation potentials of the aerofoil in a uniform stream and of the background flow pattern in the empty working section. If the background pattern is symmetrical about the centre line of the tunnel, the perturbation potential $\phi = \phi_a + \phi_b$ satisfies the boundary conditions of linearised theory for the flow past the aerofoil in the tunnel and hence, the pressure perturbation measured at any point is $p' = p'_a + p'_b$, *i.e.* the sum of the perturbation intended to be measured and the perturbation that is measured at the same point in the absence of the model*. Approximate correction for the background interference is therefore particularly simple in this case.

Assume $p'_b << p'_a$, then the absolute error in the integrand above is $2p'_a p'_b$ and the main effect on C_D arises from the values of p'_b occurring where $|p'_a|$ is largest, *i.e.* near the shocks. For a conservative estimate, consider the case where $p'_a p'_b$ has the same sign near all the shocks; a rough estimate can then be obtained by assuming $p'_b = p'_a(1 + \varepsilon/2)$, where ε = constant and represents, in fact, the relative error in C_D. For simplicity, consider a double-wedge aerofoil of thickness ratio τ at zero incidence, then the maximum of $|p'_a|$ is $\gamma M^2 \tau/(M^2 - 1)^{\frac{1}{2}}$, approximately, where γ is the ratio of the specific heats and M, the average Mach number in the empty working-section. The deviation of the background Mach number from its average is

$$M'_b = -(1 + (\gamma - 1)M^2/2)\, p'_b/(\gamma M),$$

approximately, and thus

$$|\varepsilon| = \lambda M'_b/\tau,$$

where $\lambda = 2(M^2 - 1)^{\frac{1}{2}} M^{-1} (1 + (\gamma - 1) M^2/2)^{-1}$.

M =	1·2	1·4	2	3	5
λ =	0·86	1·01	0·96	0·67	0·33

For instance, for a thickness ratio of 5 per cent., an interference error of up to 2 per cent. must be anticipated even if the Mach number variation in the empty tunnel is as low as $\pm 10^{-3}$.

It appears that, even with the best nozzles available at present, interference corrections based, *e.g.* on linearised theory are desirable for the measurement of aerodynamic forces and, moreover, that careful tunnel calibrations are required for satisfactory correction. It appears also that criteria regarding the accuracy of nozzles required for negligible interference on force measurements may generally be sought by such calculations based on linearised theory. They do not cover interference arising from viscous effects (*e.g.* influence of turbulence level on boundary layer transition[2]), but these effects do not depend on the accuracy of the nozzle.

*The same result holds for three-dimensional flow past thin wings, if the background pattern is symmetrical about the centre plane of the tunnel.

Received 19th September 1955

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Stability of Axially Loaded Continuous Beams

by

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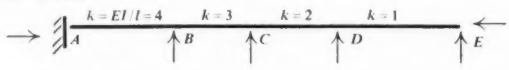
FROM Mr. A. M. Dobson's Note (July 1955 JOURNAL, page 506) which dealt with the stability of an axially loaded continuous beam, and other contacts we have had with the Aircraft Industry, it would appear that the very considerable developments of structural theory which have taken place in relation to continuous beams subjected to axial load, as employed in normal structural steel work, are not well known in aircraft stress offices. The list of references appended may then be found helpful.

The problem with which Mr. Dobson deals is very common in the structural steel world. The functions X, Y and Z, which he introduces and tabulates are simple multiples of functions s and c which are used in structural steel practice and which, at the suggestion of W. Merchant[1], have been tabulated by Livesley and Chandler[2] and are now being published by the Manchester University Press. Mr. Dobson, in his enthusiasm for these functions, in that they avoid discontinuities, has tended to a wrong emphasis in pointing out that the eigen value for a pin-ended strut is of no special significance in the general problem. His main variable u is really equal to $\pi/2\sqrt{(P/Pe)}$, where $Pe=\pi^2EI/l^2$, the pin-ended Euler critical load. Livesley and Chandler's tables are given in terms of the variable P/Pe, the value of which is of primary importance.

Among the available methods of dealing with continuous beam stability problems, two in particular come to mind. The first[3] is a type solution modification of normal Hardy-Cross or relaxation procedure. In this a moment is applied to the simply-supported end, say of a continuous beam, and a pattern of moments introduced in the two adjacent spans so as to nullify this applied moment. This procedure is applied again in the next two adjacent spans and the process continued until one arrives at the other end of the beam, as indicated in Table I. If, in this process, the moment which remains at a joint (line 6) is of opposite sign to the balancing moment applied to that joint (line 4), the beam is unstable and *vice-versa*.

EXAMPLE

Basic Data



First Load Case

P/Pe	1·20	1·10	1·00	0·90
s	2·09	2·28	2·47	2·64
c	1·25	1·11	1·00	0·91
$k \times s$	8·36	6·84	4·94	2·64

Second Load Case

P/Pe	1·80	1·50	1·20	0·90
s	0·72	1·46	2·09	2·64
c	4·50	1·97	1·25	0·91
$k \times S$	2·88	4·38	4·18	2·64

TABLE I

(*a*) FIRST LOAD CASE

	A	B		C		D		E
1. Unit moment at E							0·91	1·00
2. Balance E by rotating D					−2·05‡	−2·05†	−1·10*	−1·00
3. Balance D by rotating C			+3·44	+3·10	+2·24	+2·24		
4. Balance C by rotating B	−4·52	−3·62	−2·96	−3·29				
5. Moment remaining at B		−3·62	+0·48					
6. Total moment remaining at B			−3·14					

Total moment remaining at B (line 6) and the rotation implied by the balancing moment introduced at B (line 4) are of the same sign and the structure is therefore stable.

* $\dfrac{-1\cdot00}{0\cdot91} = -1\cdot10$ † $-\dfrac{4\cdot94\times1\cdot10}{2\cdot64} = -2\cdot05$ ‡ $-2\cdot05\times1\cdot00 = -2\cdot05$

(*b*) SECOND LOAD CASE

	A	B		C		D		E
1. Unit moment at E							0·91	1·00
2. Balance E by rotating D					−2·09	−1·74	−1·10	−1·00
3. Balance D by rotating C			+3·18	+1·62	+1·54	+1·93		
4. Balance C by rotating B	−1·60	−0·36	−0·54	−1·07				
5. Moment remaining at B		−0·36	+2·64					
6. Total moment remaining at B			+2·28					

Total moment remaining at B (line 6) and the rotation implied by the balancing moment introduced at B (line 4) are of opposite sign and the structure is therefore unstable.

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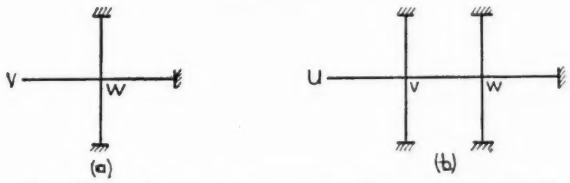
Another rapid way of dealing with the stability problem is to adopt the method of modifying stiffnesses, which has been developed in this country by R. H. Wood[4]. In this method, starting from the one end of the beam, the stiffnesses of the beams are in turn modified until, for example, one arrives at the other end of the beam. The continued appearance of positive stiffness indicates stability, and the appearance of negative stiffness, instability. Table II illustrates the type of calculations involved.

These two methods are direct in their approach and, although they have grown out of relaxation techniques, the procedure of relaxation is not involved in their application. The relaxation procedure has, however, been applied by Hoff[5] and Winter[6] to deal with problems of this kind. Hoff's approach is to apply a moment at one joint which is relaxed into the structure until there are no moments left at any constraint apart from that at which the test moment is applied. If, at this constraint the moment remaining after relaxation is of the same sign and smaller than the test moment, the beam is stable. If the moment remaining at the test constraint is of opposite sign from the test moment, the beam is exhibiting negative stiffness and has become unstable. In the region of the critical load the process tends to be rather slow in convergence. This difficulty with slow convergence is overcome in the two methods already mentioned. Physically it would appear that Wood's continued stiffness modification method which involves the evaluation of a continued fraction, should provide a simple way of evaluating the determinants which Dobson derives.

A direct approach to the stability of braced frameworks with rigid joints will be found in Ref. 7, in which the critical load is found by successive modification of the bending stiffness of members.

More difficult problems can be dealt with rapidly by extensions of these techniques using Livesley's and Chandler's tables.

TABLE II



Wood's result for the apparent stiffness of the end V of the member VW in (a) may be written as

$$(k.s)_{VW}' = (k.s.)_{VW} - \frac{(k.s.c.)_{VW}^2}{\Sigma\,(k.s.)_W}$$

The summation extends over all the members coming into W. The same formula holds for the stiffness of U in (b) provided that in the summation $(k.s.)_{VW}'$ is used in place of $(k.s.)_{VW}$.

First Load Case

	$k.s.$	$(k.s.c)^2$	$\Sigma\,(k.s.)$		$\frac{(k.s.c.)^2}{\Sigma\,(k.s.)}$	$(k.s.)'$
E			0			
			2·64	+2·64		2·64
	2·64	5·78			2·18	2·18
			0·46			0·46
D			4·94	+5·40		
	4·94	24·35			4·51	4·94
			0·43			4·51
C			6·84	+7·27		0·43
	6·84	57·87			7·95	6·84
			−1·11			7·95
B			8·36	+7·25		−1·11
	8·36	109·0				
A						

Effective joint stiffnesses $=\Sigma\,(k.s.)$ are always positive. Therefore the beam is stable.

Second Load Case

	$k.s.$	$(k.s.c)^2$	$\Sigma\,(k.s.)$		$\frac{(k.s.c.)^2}{\Sigma\,(k.s.)}$	$(k.s.)'$
E			0			
			2·64	+2·64		2·64
	2·64	5·78			2·18	2·18
			0·46			0·46
D			4·18	+4·64		
	4·18	27·2			5·87	4·18
			−1·69			5·87
C			4·38	+2·68		−1·69
	4·38	74·4			27·7	4·38
			−23·32			27·7
B			+2·88	−20·44		−23·32
	2·88					
A						

Effective stiffness of joint B is negative and the beam is unstable.

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A Resonance Chart for Damped Vibration

by

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A CONVENIENT METHOD is pointed out for calculating the response of a damped linear system with one degree of freedom to harmonic excitation. Results of such calculations are usually represented by the familiar "resonance curves"—one curve being plotted for each intensity of damping. These curves are not particularly convenient to use and Yates[1] has overcome several of their defects by throwing them into a nomographic form. Yates' nomogram is based upon the concept of viscous damping and it does not give the information of a conventional set of resonance curves in that it relates to the velocity of vibration. By changing over to hysteretic damping[2], a nomogram of somewhat similar form may be constructed such that it gives amplitudes and phase angles of displacements while retaining the advantages, over resonance curves, of this form of representation.

Notation

E	energy dissipated per cycle
F	amplitude of applied force
h	hysteretic damping coefficient
i	$=\sqrt{(-1)}$
k	spring stiffness
M	mass
n	magnification factor
Q	dimensionless measure of damping $(=1/\mu)$
R	amplitude of displacement x
T	kinetic energy
t	time
V	potential energy
x	displacement
η	phase angle between harmonic displacement and applied harmonic force
μ	dimensionless measure of damping $(=h/k)$
ω	excitation frequency
ω_1	natural frequency $=\sqrt{(k/M)}$

1. PRELIMINARY THEORY

It was shown in a previous paper that the steady harmonic motion of a damped system having one degree of freedom is governed by

$$M\ddot{x}+\frac{h}{\omega}\dot{x}+kx=Fe^{i\omega t} \quad . \quad . \quad (1)$$

or, alternatively,

$$M\ddot{x}+k\,(1+i\mu)\,x=Fe^{i\omega t}. \quad . \quad . \quad (2)$$

To fix ideas, M may be regarded as the mass of a rigid body which is suspended by a light spring of stiffness k, the spring embodying hysteretic damping such that the damping coefficient is h. The displacement is x and $\mu=h/k$. If a solution of these equations is now sought in which x varies with the driving frequency ω, it is found that

$$x=\left[\frac{e^{-i\eta}}{\{(k-M\omega^2)^2+h^2\}^{\frac{1}{2}}}\right]Fe^{i\omega t} \quad . \quad (3)$$

where the phase angle η is given by

$$\eta=\tan^{-1}\left(\frac{h}{k-M\omega^2}\right)=\tan^{-1}\left(\frac{\mu}{1-\omega^2/\omega_1{}^2}\right). \quad (4)$$

The complex quantity within the square brackets of equation (3) is of the nature of a "receptance."

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It is common in vibration theory to introduce the notion of a "magnification factor" n. This is a measure of the increase of the displacement $Fe^{i\omega t}/k$ which is a result of the motion. That is to say

$$x=n\cdot\frac{F}{k}e^{i(\omega t-\eta)} \quad . \quad . \quad . \quad (5)$$

where

$$n=\frac{1}{\left[\left(1-\frac{\omega^2}{\omega_1{}^2}\right)^2+\mu^2\right]^{\frac{1}{2}}} \quad . \quad . \quad . \quad (6)$$

Now it will be seen that n and η are both functions only of the non-dimensional quantities μ and ω/ω_1. It follows therefore that curves may be drawn which are similar to the familiar "resonance curves" of viscous damping theory; they are curves of n and η plotted against ω/ω_1 for various values of μ. Curves of this sort have been presented previously[2].

These resonance curves afford an excellent insight into the nature of forced harmonic motion. But they are not particularly useful when one comes to make practical calculations. This is because most engineering systems in which vibration is troublesome possess values of μ which are smaller than 0·1 and values of 0·001 are not uncommon*. This means that each resonance curve contains a high peak which cannot be drawn without sacrifice of accuracy lower down; this difficulty is aggravated by the sharpness of the peak. Moreover, the height of the peak depends very sensitively upon the value of μ.

By the use of a nomogram (or "alignment diagram"), Yates has presented a method of showing the relationship between the magnification (although not through a magnification factor of the same type as n above), the phase angle, the frequency and the damping[1]. This overcomes the difficulties mentioned above and has the added advantage of permitting a continuous scale to be used for the damping. Now Yates' nomogram refers to the variation, not of displacement x but of velocity $\dot{x}$. That is to say, his measure of magnification relates to the amplitude of the velocity and his phase angle is that between the velocity and the impressed excitation. This is an outcome of his basing his theory on the concept of viscous damping.

The purpose of this note is to show how Yates' method of presenting a universal resonance chart can be adapted to give the magnification and phase *of displacement*; for these quantities are much more widely used. This is accomplished by throwing the results (4) and (6), for hysteretic damping, into the nomographic form.

2. THE CONCEPT OF A Q-FACTOR IN HYSTERETIC DAMPING

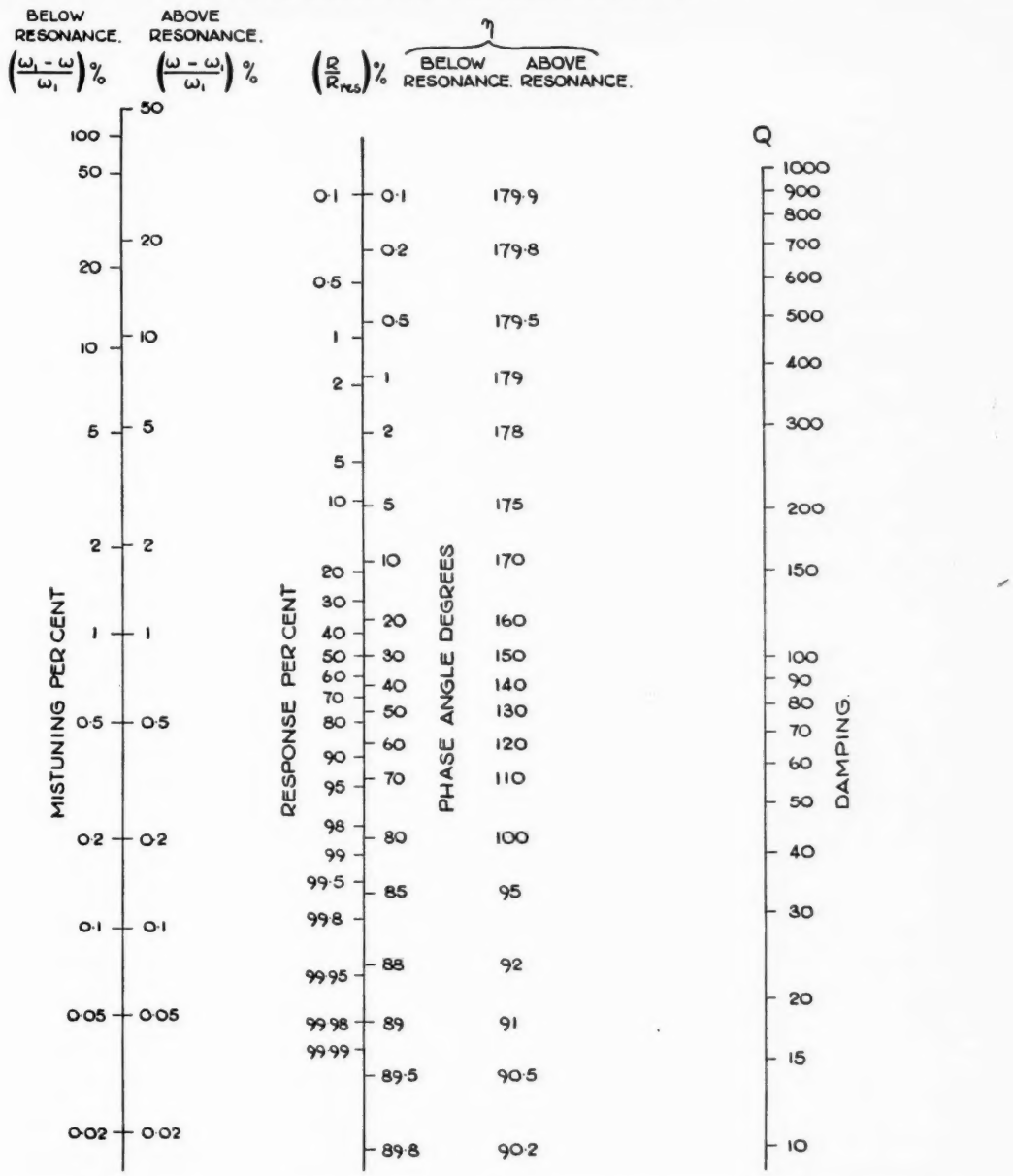
The energy dissipated per cycle by a system whose equation of motion is (1) or (2) is given by

$$E=\int_0^{2\pi/\omega}\frac{h}{\omega}\dot{x}^2dt=h\pi R^2 \quad . \quad . \quad . \quad (7)$$

where R is the amplitude of x and ω is its frequency of variation[2].

*The physical (as opposed to the mathematical) meaning of this will be discussed in the next section.

RESONANCE CHART FOR HYSTERETIC DAMPING



The maximum kinetic energy of the system when ω has the resonance value ω_1 is equal to the maximum potential energy at that frequency. That is to say,

$$T_{max} = \tfrac{1}{2}M(R\omega_1)^2 = \frac{kR^2}{2} = V_{max}. \quad . \quad (8)$$

It is becoming increasingly common for the ratio of this energy to the energy dissipated per cycle to be used to define a dimensionless measure of damping which is called the "Q-factor" of the system; thus

$$\frac{T_{max}}{E} = \frac{1}{2\pi} \cdot Q. \quad . \quad . \quad . \quad (9)$$

This quantity Q is a convenient measure of the freedom of the system from damping.

The Q-factor of the system that is discussed in this paper is evidently given by

$$\frac{T_{max}}{E} = \frac{kR^2}{2} \cdot \frac{1}{h\pi R^2} = \frac{1}{2\pi}\left(\frac{k}{h}\right). \quad . \quad (10)$$

It follows that, for hysteretic damping of the simple system having one degree of freedom,

$$Q = \frac{k}{h} = \frac{1}{\mu}. \quad . \quad . \quad . \quad (11)$$

The notion of a Q-factor is borrowed from electrical theory and it is becoming more and more widely used in vibration theory. The concept will be used in this paper simply to conform with what is becoming a standard practice. As is evident from equation (11), there is no

particular merit in using Q instead of μ as a dimensionless measure of damping—one is the reciprocal of the other.

It may be mentioned that the amplitude of the system in its resonant condition is given by

$$R_{res} = \frac{F}{h} = Q\frac{F}{k}. \quad . \quad . \quad (12)$$

Thus Q is the magnification factor of the system at resonance.

3. THE CALCULATION OF RESPONSES

It is clear that, for specified values of ω/ω_1 and μ, the values of the magnification and phase angle can be calculated from equations (4) and (6). It is convenient for the purpose of calculation, however, to rearrange these equations slightly before doing so.

From equation (4) it is seen that

$$\cot\eta = \frac{k - M\omega^2}{h} = Q\left(1 - \frac{M\omega^2}{Qh}\right). \quad . \quad (13)$$

so that

$$\cot\eta = Q\left(1 - \frac{\omega^2}{\omega_1^2}\right). \quad . \quad . \quad (14)$$

This relationship between η, Q and ω/ω_1 can be shown in nomographic form, as in the accompanying chart. A straight-edge laid across the scales gives directly the related values of these three quantities. In drawing up the nomogram it is convenient, not to refer directly to the frequency ratio ω/ω_1 but to the percentage mistuning [namely $(\omega_1 - \omega) \times 100/\omega_1$ below resonance and $(\omega - \omega_1) \times 100/\omega_1$ above resonance].

Instead of comparing the amplitude of x with the amplitude F/k which corresponds to very low frequency excitation and very small damping (and so arriving at the notion of the factor n), the amplitude may be compared with that at resonance. If the amplitude is R, then

$$\frac{R}{R_{res}} = \left(\frac{F}{[(k - M\omega^2)^2 + h^2]^{\frac{1}{2}}}\right) \Big/ \left(\frac{F}{h}\right) = \frac{h}{[(k - M\omega^2)^2 + h^2]^{\frac{1}{2}}}$$

. . . . . (15)

In view of the relation (13), this may be written simply as

$$\frac{R}{R_{res}} = \sin\eta. \quad . \quad . \quad . \quad (16)$$

Therefore the ratio R/R_{res} may be read directly off the nomogram by means of a suitable calibration of the η-line; on the chart, this fraction is expressed as a percentage.

To use the chart, it is only necessary to join with a straight-edge the reading on the left-hand line which indicates the mistuning to the required value of Q on the right-hand line. The intersection with the middle line gives both the phase angle η and the response.

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On the Elimination of Structural Discontinuities

by

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(Professor of Aeronautical Structures, Imperial College of Science and Technology)

THE EFFECT of discontinuities on the analysis of structures is discussed by W. J. Goodey in a Technical Note in the October JOURNAL[1]. He quite rightly points out that a structure with cut-outs is more difficult to analyse (especially for routine calculations) than a structure without cut-outs. Subsequently he indicates a procedure for obviating the former complications by introducing fictitious members in place of the cut-outs. Using then the variational method of arbitrary multipliers he derives the stress distribution in the structure with cut-outs from the simpler analysis of the structure without cut-outs.

Now, I am particularly interested in Mr. Goodey's suggestions for *an identical* method has already been published in the March 1955 issue of "Aircraft Engineering"[2] under the sub-title "A new approach to the problems of cut-outs" (page 87). The only difference is that there a more obvious physical approach is used by introducing such initial strains H in the fictitious elements that their stresses are zero, *i.e.* that they are effectively non-existent. This initial strain matrix H is, in fact, Goodey's column matrix of unknown multipliers λ.

Reference 1 also mentions that the calculation of the matrices of the coefficients A, B, C is a subject by itself and may be described as an art. While agreeing most wholeheartedly with Mr. Goodey, I should venture to point out that these aspects are discussed at some length in the February, March, April and May issues of "Aircraft Engineering" and illustrated extensively on wings. Reference 2 shows in fact how these coefficients may be calculated in a systematic manner, either on a desk computor or more preferably and quickly on a digital computor.

The following more detailed comparison may be of interest:

Thus Goodey's equation (5) is contained in the equation immediately preceding equation (262) (page 87 of Ref. 2). Furthermore, his equation (6) is the same as equation (267) and his (7) is included in (268).

The above method of the elimination matrix H is repeatedly referred to in the March, April and May issues of "Aircraft Engineering." I note here its prominent display on page 94. Finally, the theory is illustrated by a numerical example in the May issue, page 154 and Fig. 69.

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See also corrections of misprints on page 158, May, and page 255, August 1955.

W. J. GOODEY

The method of dealing with structural discontinuities discussed in my Technical Note in the October JOURNAL 1955 is indeed the same as that of Professor Argyris recently published in "Aircraft Engineering," though the derivation and the suggested scheme for solving the equations are different. I had not read Professor Argyris' papers when I wrote my Note, or I should, of course, have made reference to his work.

The almost simultaneous discovery of the same theorem by workers in the same field is, of course, not an uncommon occurrence, and it may be of interest if I recall something of the history of the method on my side. As I suggested in my Note, the analysis of highly redundant structures is to some extent an art, since there is considerable freedom of choice in regard to the internal self-equilibrating systems. This led me some years ago to consider whether it might be worth while to develop a method which would not depend on any particular choice of redundancies, and the following theorem was the result. Assume the Strain Energy of a structure to be expressed in the form $U=X'AX$, where X is a column of generalised forces, at present unknown, but sufficient to specify the stress distribution in the structure. The quantities in X are subject to certain conditions given by the equation

$$BX+C=0. \quad . \quad . \quad . \quad (1)$$

The method of arbitrary multipliers then shows that for U to be a minimum, subject to the given conditions, we must have

$$AX+B'\lambda=0, \quad . \quad . \quad . \quad (2)$$

λ being the column of multipliers.

For example, for a pin-jointed framework, X could be the column of loads in the individual members. The matrix A would then be simply a diagonal, and equation (1) the set of equilibrium equations for each joint, which could be written down immediately from the geometry of the structure. The matrix C would be the column of applied loads, and λ the column of joint deflections. Thus the solution of equations (1) and (2) gives the loads in all the members and the deflection of all the joints (relative to some fixed plane).

I have not developed this method, but it appears to bear a strong resemblance to the deflection method outlined by Dr. Williams in his lecture on "Recent Developments in the Structural Approach to Aeroelastic Problems," published in June JOURNAL 1954.

Later, arising from this idea of making U a minimum subject to certain restrictions, I evolved the method for the treatment of cut-outs given in my recent Technical Note. The method is particularly effective for the treatment of cut-outs in a circular fuselage, and has been applied to analyse the effect of window openings, and of a large cut-out, in this type of structure.

PROFESSOR ARGYRIS

With reference to the theorem stated in Mr. Goodey's second paragraph I should like to point out that it expresses just *one* aspect of the duality of the force and displacement methods. Its complete exposition will be found in Table II of the March 1955 issue of *Aircraft Engineering*, pp. 90-94. All relevant theorems are given there, including those referring to generalised forces and displacements.

Instability of Integral Panels

by

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THE PAPER[1] by Dr. A. H. Chilver (October 1955 JOURNAL) purposed "to present alternative theoretical approaches to the problem of local instability of a simple type of panel with unflanged stiffeners."

Examination of these alternative approaches reveals that they are in fact identical and are based on the same approximate representation of the buckled form of the plate by sinusoidally varying lengthwise and transverse deflection, and of the stiffener by sinusoidally varying twist. The difference in the results obtained by Dr. Chilver is explained by the fact that whereas in the first analysis he uses plate theory correctly to express the strain energy in the stiffener, in his second analysis he omits entirely the torsion-bending energy. Thus if Dr. Chilver's equation (21) is correctly written in the form[2],

$$U_1=\tfrac{1}{2}GJ\int_0^L\left(\frac{d\theta}{dx}\right)^2 dx+\tfrac{1}{2}E\Gamma'\int_0^L\left(\frac{d^2\theta}{dx^2}\right)^2 dx \quad . \quad (1)$$

it will be found that his equations (15) and (24) are identical.

The warping constant Γ' in the present case is entirely composed of the secondary constant Γ_2 (*see* Ref. 2, p. 126) which, in the notation of the paper, is

$$\Gamma_2=\frac{b_1^3t_1^3}{36(1-\nu^2)}. \quad . \quad . \quad (2)$$

Incidentally, Dr. Chilver's equation (15) is in fact identical with that given by Mr. Kelsey[3] in his very lucid

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criticism of the paper by Dr. Yusuff; as stated by Mr. Kelsey there is little point in using the approximate method when the exact solution is readily available[4].

With reference to Dr. Chilver's equation (29) it may be noted that a very similar form of empirical formula for the local buckling failure of struts was developed by the N.A.C.A. from numerous tests (*see* Ref. 2, p. 171). Thus in Dr. Chilver's notation the two equations would be

$$\sigma_{max} = 0{\cdot}863\,(\sigma_Y{}^2\sigma_{cr})^{\frac{1}{3}} \quad . \quad \text{(Chilver's (29))}$$

$$\sigma_{max} = 0{\cdot}9\,(\sigma_Y{}^3\sigma_{cr})^{\frac{1}{4}} \quad \text{(N.A.C.A. with } C = 0{\cdot}9\text{)}$$

Using the same two examples as are given in Table II of Dr. Chilver's paper, but calculating σ_{cr} by means of Fig. 2 of Mr. Catchpole's paper[4] the following results are obtained.

	σ_{cr} lb./in.^{2}	σ_{max} lb./in.^{2}		
		Chilver	*N.A.C.A.*	*Test*
Panel E.	34,600	54,800	61,700	60,000
Panel 1B.	55,500	63,400	69,400	69,000

The constant C in the N.A.C.A. formula tends to decrease with the ratio

Initial instability stress/Proof stress

so that it may be expected that the calculated failing stress for Panel E would be an overestimate.

A final point on the matter of nomenclature needs making. If the torsional mode of instability is understood to be that involving rotation of the stiffener about a longitudinal axis with no distortion of the cross-section (*see* Ref. 2, p. 153), then in both the methods considered by Dr. Chilver the assumed mode of deformation would properly be called torsional. Once the mode is fixed any differences in the final formulae obtained must be due to mathematical and not physical reasons.

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A. H. CHILVER

MR. P. C. DUNNE has made a very valuable contribution to the discussion on local instability in integral panels. In an earlier note Mr. Kelsey has pointed out the largely fortuitous agreement between Dr. Yusuff's theory of torsional instability and test results. In my own paper, I indicated the limitations of Dr. Yusuff's theory, and working on his basic assumptions showed that the problem could be treated as one of simple local instability; I intended to convey by implication that a neglect of the warping stiffness of the flanges of the panel leads to a buckling stress which is lower than the true local buckling stress.

As Mr. Dunne points out, and as one would expect, the inclusion of a warping term in the torsional strain energy of the flanges leads to the same buckling stress, whether the problem is treated as one of torsional or local instability. This is an important conclusion, and confirms that both methods of analysis, when treated fully, are correct.

Some interesting points arise from Mr. Dunne's note; firstly, he confirms that Dr. Yusuff's test results can be explained on the basis of conventional local instability theory; secondly, he shows the importance of post-buckling strength. The collapse stresses put forward in my own paper are more conservative than those given by the N.A.C.A. formula; both estimates are in good agreement with test results. Mr. Dunne's analysis implies also that the approximate local buckling stresses given in my own paper are in good agreement with the exact values calculated by Mr. Catchpole.

The conclusions to be drawn from the discussions of Dr. Yusuff's orginal paper are:—

(*i*) the correct buckling stress may be derived by both "local" and "torsional" analysis, provided the "torsional" analysis takes into account warping effects; and

(*ii*) test results are fully explained by considering the post-buckling strength of the panels.

19th November 1955.

THE LIBRARY

Reviews

THE DIRECTION OF WAR. *Air Vice-Marshal E. J. Kingston-McCloughry. Jonathan Cape, 1955. 261 pp. 16s.*

Air Vice-Marshal Kingston-McCloughry's book gets off to a very slow start, but soon becomes extremely interesting reading, and his summary at the end is valuable and informative. It has from the point of view of the ordinary reader certain faults, the biggest of which is the rapid switching from considerations of policy and practice in the art of war planning to the interplay of characters and personalities. In the result the reader is sometimes confused in his attempt to follow the general argument, in which there is a mass of detail. This detail, I feel sure, is hardly comprehensible to the layman. There is one other considerable fault which is the omission to study the planning and execution of operations at sea, particularly in relation to the protection of trade. This is a vast subject which merits at least some reference in a book of this sort.

On the whole I agree with his evaluation of the characters and qualities of the war leaders, whom he both criticises and praises, and I am particularly interested in his appreciation of Sir Trafford Leigh-Mallory's ability. The author says that if Leigh-Mallory had been given full scope, he would have risen to great heights as a commander in the field. It is understandable that when working under such dominating characters as the top commanders in the invasion of France, L.-M. found himself hampered and conscribed. It is all the more sad that his death in a flying accident robbed him of the task of commanding the Allied Air Forces of South East Asia Command.

The book will undoubtedly find its place in Staff College libraries, where it will be a valuable contribution to the numerous other studies of the higher direction of war.—P. B. JOUBERT.

THE STARS AT NOON. *Jacqueline Cochran. Robert Hale, London, 1955. 274 pp. Illustrated. 15s.*

Jacqueline Cochran's flying career was remarkable from the start. In her early twenties she joined a flying school and went solo on the third day. The engine quit on her first solo, but, as on so many subsequent flights, her landing was safe. Within two years she was competing in the Mildenhall to Melbourne 1934 air race. The last twenty years she has spent in organising women's flying services, air racing, experimental flying culminating in the first supersonic flight by a woman, several world speed records and an F.A.I. Gold Medal.

Biographies of famous pilots often reveal a childhood and private life so undistinguished that a dozen pages suffice to describe them. Even if "Jackie Cochran" had never flown, the extraordinary story of her life would be well worth reading. Living in dire poverty in the deep South, she left school at eight and worked twelve hours a day in a cotton mill. At nine she was a forewoman, at ten a union member on strike. She then left the textile industry and joined a beauty shop. Her cosmetics business today turns over millions of dollars and in 1954 she was chosen as America's outstanding business woman.

At eight years of age she delivered babies ("before I even knew that the stork was a bird") and, in spite of only two years' schooling, later qualified as a nurse. Her husband, Floyd Odlum, has helped her to write this story because, as she says, "a semicolon is still, to me, a small intestine."

In recent years her interests have been political. Floyd coined the phrase "I like Ike" and they ran the campaign which succeeded in persuading General Eisenhower to stand for the Presidency. This was just after Jacqueline had refused nomination as a *Democrat* Congresswoman. On her world tours she has been fêted by Generals and consulted by heads of states from the Pope to Peron. Her only setback seems to have been at the Kremlin. "I smiled my sweetest at the guard. He smiled back, but when I took a step forward toward the open gate, he cocked his gun."

It is a far cry from the ragged, starving child to supersonic flying and dining with Cardinals and Presidents. Jacqueline Cochran's story is a vivid reminder of the power which flows from determination.—A. H. YATES.

THE SKY MY KINGDOM. *Hanna Reitsch. Bodley Head, London, 1955. 222 pp. Illustrated. 12s. 6d.*

It is no longer unusual to find a test pilot writing an autobiography while still in the early thirties. Women test pilots are, however, rareties and Hanna Reitsch may well be the greatest woman pilot in the world. She wrote her story shortly after the war ended but it has only now been translated and issued in Britain.

It is difficult to read without prejudice of the life of the girl who was one of the last to talk to Hitler in his bunker, the friend of Himmler and Goering and the organiser of the suicide pilots who were to bomb us late in the war. This is the woman who writes indignantly of the "degradation of captivity" when detained by the Americans in 1945 shortly after they had relieved Belsen. Perhaps they found it difficult to understand how one who was an intimate of the Nazi leader and had been since youth a flying ambassadress for Germany could be quite so innocent.

Hanna was lucky in that her home in the early nineteen thirties was close to a leading gliding club. While studying to be a doctor she was taught to glide by Wolf Hirth and became fascinated. She rapidly became one of the world's leading sailplane pilots and visited South America, the U.S.A., Finland and Africa on state subsidised visits to demonstrate German prowess in gliding. Her ability as a pilot was such that she was soon a Government test pilot on powered aeroplanes. In 1937 she demonstrated the Focke helicopter inside the Deutschland-halle in Berlin. Her wartime work included flight testing of dive brakes and balloon barrage cutting devices and the test flying of the rocket driven Messerschmidt 163. While attempting a landing with the wheel still hanging on she suffered very severe injuries in this aeroplane. Within a few months she was back flying the piloted V1 and the proposed suicide bomb. We were spared an onslaught by the suicide squad mainly by the advance of the Allied armies, but partly because Hanna's friends in the Government failed, for once, to appreciate the worth of her idea.

There has never been so versatile a woman pilot, nor one entrusted with such important test flying. When the war ended Hanna Reitsch was only thirty-two and it was inevitable that she should again fly for Germany in the World Gliding Championships in Madrid in 1952 (after this book was written). There a Briton won the world

title for the first time. The news was headlined in a leading British paper as "V1 Hanna loses"! Such is the power and influence of this extraordinary woman.—A. H. YATES.

AGAINST THE SUN—THE STORY OF WING COMMANDER ROLAND BEAMONT. *Edward Lanchbery. Cassell, 1955. 270 pp. Illustrated. 16s.*

Beamont has been Chief Test Pilot for English Electric since 1947 and he has there been called upon to fly two exceptional aeroplanes: the Canberra, the bomber which performs like a fighter, and the P1, Britain's first straight and level supersonic fighter. The spectacular performance of these aircraft has ensured him a place in the public eye and explains this biography by Edward Lanchbery.

The book devotes two-thirds of its length to the story of Beamont's distinguished war record. He learned to fly just in time to go to France in 1939 and flew fighters until he was shot down and taken prisoner in Germany six months before the European war ended. That this lively narrative of day and night fighting in Hurricane and Tempest, of "train-busting" and V1 interception, is in such detail is due, one suspects to Beamont's habit of diary writing. The war ended with Wing Commander Beamont at the ripe old age of twenty-five, thinking of civilian employment as a test pilot. In many ways his qualifications were unusual. The first 19 years of his life are passed over in four pages but include the story of a trip in an Avro 504 at the age of six (almost a "must" for this generation of test pilots). Beamont's mediocre school record and the fifteen hours he took to go solo had been forgotten in the brilliance of his Service record, but the lack of a Test Pilots' School course and of flying experience on heavy aeroplanes were certainly unusual qualifications for the test pilot of a new bomber. However, exceptional aeroplanes deserve exceptional pilots and all has gone well.

Mr. Lanchbery is least happy in interpreting the technical information given to him by Wing Commander Beamont. In spite of some odd statements about shock waves travelling "backwards along the flight path" and of air ceasing to be fluid at the speed of sound, there are some interesting revelations about high speed flying.

The story of Beamont's unexpected Mach one flight at Muroc in May 1948 is told in full. Beamont now accepts that position error misled him, that his dive was not quite supersonic and that Derry was the first British pilot to exceed the speed of sound in September 1948. Position error again misled Beamont on the early flights of the P1: this time it transpired that an apparently subsonic flight was, in fact, supersonic.

What happens to the sonic bangs when the aeroplane is supersonic in level flight is explained. The shock wave sounds "like the rumble of a train over an area a few miles wide on either side of the aircraft's track." That the shock wave might be focused into a loud bang by a temperature inversion in the atmosphere was predicted two or three years ago, but was first experienced, we learn, in February 1955.—A. H. YATES.

LION WITH BLUE WINGS: THE STORY OF THE GLIDER PILOT REGIMENT 1942-1945. *Ronald Seth. Gollancz, 1955. 246 pp. 16 plates. 16s.*

This is the story of the Glider Pilot Regiment which flew and fought in every European campaign between 1942 and 1945. The Army glider pilots never numbered more than 5,000, but the novelty of their role and of their weapon directed attention to them.

The chiefs of Staff first awoke to the possibilities of military gliders when, in the early summer of 1940, the Germans captured the Fort of Eben-Emael by landing troops on its roof in gliders. In the midst of our preoccupation with defence the first steps were taken then to plan this purely aggressive weapon—the military glider. The eight-seat General Aircraft Hotspur, the thirty-seat Airspeed Horsa and the tank-carrying General Aircraft Hamilcar all eventually saw service with the Glider Pilot Regiment, but only after a tremendous effort had been made in research, design and development both in the Industry and in the Ministry of Aircraft Production. This work, which went on simultaneously with the building of the Regiment, is scarcely mentioned by Mr. Seth although it is of prime interest to those working in aviation. The author, who was a Royal Air Force officer, was a prisoner of war from 1942 to 1945 and has compiled this history from the Regimental records and from talks with its leaders. Perhaps as a result the aeronautical descriptions are rather sketchy. The R.A.E. and the Airborne Forces Experimental Establishments are scarcely mentioned. It was at these places that the experiments were made with twin tug towing, rocket assistance to tug and glider, blind towing, glider automatic pilots, glider dive parachutes, snatch pick-up and so on. The pilots in these tests were from the R.A.F. and the Glider Pilot Regiment, but the other crew members were the civil servants who planned the experiments. Mr. Seth mentions the tests briefly, but attributes the entire work to an R.A.F. team at Farnborough. Even the Commanding Officer's name is given wrongly.

The tactical use of the gliders is well described. In view of the lack of experience with the weapon it is surprising that Sicily should have been chosen for the first major operation. The bad weather could not have been foreseen but the unsuitable terrain, the unfamiliar gliders, tugs and towing crews made things difficult for the Regiment from the outset. Of the 137 gliders taking part on 9th July 1943 only ten were British Horsas. The rest were the American Waco Hadrian and the tugs were mainly Dakotas. The American crews refused to tow within 3,000 yards of the coastline and forty-seven gliders came down in the sea. Few of the rest reached their target. In both this operation and in the later, highly successful, landings in Normandy, Holland and Germany the story of courage and resourcefulness is unbroken. The motto "Nothing is impossible" was well chosen.—A. H. YATES.

HIGH SPEED INTERNAL COMBUSTION ENGINES. *Arthur W. Judge. Chapman & Hall Ltd., London, 1955. 494 pp. Illustrated. 75s. (Fourth Ed.)*

In reviewing the Fourth Edition of this book which has found a place on the bookshelf of test engineers for so long, one is impressed by the wealth of detail, plates and diagrams. Closer investigation shows that many of the experiments described are between 30 and 50 years old and can hardly be said to apply to high speed engines as we know them today.

There is also too much space spent in repetitive description of similar equipment mainly from makers' descriptive brochures and the space would be better used to give basic measuring data and good testing practice on engines in general. The problems are generally similar on Petrol, Diesel, Aircraft and Gas Turbine engines, in that we are concerned with the accurate measurement of air flow, speeds, power, pressures, flows, temperatures and stresses, and so on, and those skilled in the testing of Petrol engines have had little difficulty in changing to the Gas Turbine.

Chapter 1. Some of the data relates to engines of lower compression ratio than is generally used today. No reference is made to general principles as applied to gas turbines.
Chapter 2. One always thought that the main point in favour of using gas for "running in" piston engines was to obviate washing the oil from the walls in the initial light running. There is too much description of diverse test houses and too little on test procedure.
Chapter 3. This soon becomes a catalogue of instruments which should be mentioned as a means, but be described in the chapter on instrumentation.
Chapter 4. This is a most important chapter on the measurement of air flow and deserves a better theoretical treatment. Some of the experimental methods date back to 1906 and it would have been better to quote B.S.S.1042 Flow Measurement 1943.
Chapter 6. Again this chapter gives all that is needed in the first few pages then proceeds as an elementary heat engine's book, through "Prony" brakes and various brakes not now made and becomes descriptive literature for the makers of dynamometers.

The paragraph on supercharger tests must not be taken as an axiom. It is only necessary to test aero engine superchargers during development to obtain the characteristic curves at various tip speeds and acceptance tests of subsequent units can quite well be done on the engine. The method described was just an expensive whim.
Chapter 7. Much space is devoted to instruments not really suited to high speed and surely today one need only describe electronic pressure measuring devices, except where describing normal pressure gauges and manometers, which are not mentioned in detail.
Chapter 8. The title Cathode Ray Indicators is a misleading title and Electronic Measuring Technique would be preferable. In describing the various types of pressure pick-up elements it is stated that the condenser type does not require water cooling; it is our experience that they not only need water cooling but it is preferable to insert a water jacket between pick-up and the test feature to reduce pick-up and body distortions. While this introduces cavity resonances it does make the results from the pick-up more accurate.

In the paragraph on vibration testing, only crystal pick-ups are mentioned and in many applications are totally unsuitable. Mention should be made of velocity-conscious seismic pick-ups or accelerations pick-ups, both of which are widely used. No mention is made of the use of capacity and inductance pick-ups. Particularly in gas turbines, a large proportion of measurements are carried out using strain gauges, both for steady and fluctuating stress measurement. No reference is made to these methods.
Chapter 9. From the engine speeds quoted these results have no bearing on high speed I.C. engines and surely today, other than in the school laboratory, one would employ electronic measuring techniques.
Chapter 10. After leading us through low speed engine history we come to the paragraph on thermocouples and Fig. 278 gives E.M.F.'s-temperature difference. On the following page (332) a tabulated list in Table XV does not line up with the data on Fig. 278 and is incorrect regarding the E.M.F. for Plat./Rh and Hoskins or Chrom./Alumel. On page 334 a further table of E.M.F.-temperature relationships gives the better values.

It is stated that a 'couple as Fig. 280 has minimum errors due to conduction. It is hard to see why, as it has longer exposed leads than Fig. 281. The necessity to employ thin leads is to obtain quick response to change of temperature and is not explained.

Chapter 12. It is odd that whereas the bulk of the book deals with the research and development aspect of engines the chapter on aero engine testing deals very largely with hangar testing with an airscrew load. Most development testing and all power calibrations are carried out on a dynamometer.

Of the hangar layouts in Fig. 336 only item "C" is to be recommended and this is improved if done as in Fig. 338.

The fuel system shown in Fig. 337 is not to be recommended in this country where we go to much trouble to keep water out of our tanks and prefer to pump fuel either direct to the engine or to a header tank.

No data is given on the various testing methods used in the development of supercharged aero engine, such as altitude rating curves, ignition, consumption loops, and so on. The altitude plant described was wrecked in 1923.
Chapter 13. *Gas Turbine testing.* The statement that the "range of pressures and temperatures is considerably greater in the reciprocating engine than in the modern constant pressure gas turbine," is today outmoded.

In the paragraph on high negative work, reference is made to the need for large dynamometers to measure the turbine power. In practice it is usual to scale down the turbine to suit available dynamos and air flows. It is also usual to run the turbine at the temperatures available from the compressor supplying the air and to correct the running speeds to $N/\sqrt{T}$ as obtained in the "hot" case.

Table 18 seems to be in some error; it is not clear to what the second line of figures entitled "Compressor" refer. Similarly, it is usual to have several pounds pressure loss in the combustion chamber.
Pressure Measurements. It is more usual to have a "wall static" than the open ended tube shown at (*a*). For practical considerations it is also usual to use a straight total head tube with a blank end and a small hole (about 0·032 in.) in the upstream side, rather than the 90° tube shown. To measure the dynamic head, again practical considerations often prevent the type of instrument shown from being used.
Fuel Quantity Measurements. The method given in (1) is only useful for very small engines or combustion rigs. The second method in conjunction with an automatic timer using a Post Office relay is best. With present engines it is usual to time 20 gallons to get a reasonable time reading.
Fuel Measurement Check Tests. This method is not good enough as engine speed is likely to change if the fuel inlet pressure drops appreciably and 20 galls. is the order of timing quantity needed. It is more usual to calibrate the meter in the strument department against a calibrated tank.
Exhaust Gas Temperatures. Although the Foster galvanometers described have served well, precise measurement has become so important that the change has been made to potentiometers.
Suppressed Zero Jet Pipe Thermocouples. It is not usual to use these on test work.
Compressor Unit Tests. It is usual to test compressors during research and development only and not on series engines.
Testing Complete Gas Turbines. It is incorrect that the R.R. air intakes have hexagonal ducts. They are in common with the Bristol ones mentioned, acoustically lined splitters with a number of bends so that the noise impinges on the surfaces and cannot "see through." The silencer will entrain anything between 0·8 and 5 times engine air flow. The silencer shown on Fig. 368 entrains around 5 times engine air flow.
Turbine Exhaust Arrangements. The silencers mentioned are now obsolete and largely replaced by Mk.V and Mk.VI

Cullum Detuners. It is untrue to say that the Cullum Detuner has no diffuser.

Test cells should be so constructed, when possible, that the air flow is straight through, in one plane, front to rear and not as in Fig. 356. The U-shaped cells as on Fig. 357 are bad in that hot air discharged upwards is often carried into the inlet. This has been the cause of much trouble in U.S.A. Close scrutiny of Figs. 358-9 will show that they are in fact different cells.

Thrust Measuring. Hydraulic Force Method. It is incorrectly stated that the cylinder is filled with completely aerated liquid. Obviously it should read de-aerated liquid.

Chapter 14. This is again largely a collection of makers descriptive data and it is considered that if instrumentation had been wholly covered in a single chapter rather than in each chapter, often with repetition, the book could have been much shorter.—F. GREAVES.

FASTEN YOUR LAPSTRAPS. *Geoffrey Willans. Max Parrish, London, 1955. 112 pp. Illust. by David Mathias. 9s. 6d.*

I think it would be a very good idea if the Corporations were to give away a copy of this book to every cash customer. Those who have read "Down with Skool" and "How to be Topp" will know the sort of writer Mr. Willans is and if the humour may seem a little strained at times it is still a book that will pass an amusing hour of travel—particularly, of course, air travel. All types with whom the passenger is likely to come in contact are subjected to "Mike taking"—the fellow-traveller (in the pre-Iron Curtain sense), the wizard prang pilot and even the customs officials—which is quite an effort when you think how humour-devoid customs can be. The illustrations match up to the text—but I do miss Searle.—F.H.S.

SQUADRON AIRBORNE. *Elleston Trevor. Heinemann, London, 1955. 256 pp. 13s. 6d.*

The setting of the novel is a Fighter Station in Southern England during the Battle of Britain. It is a well-told story, but there have been some excellent personal accounts of this phase of the war and a fictional description has not, in this case, the interest or excitement which is conveyed by a record of true experience.—F.H.S.

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Reports

AERODYNAMICS

Boundary Layer

*Downstream effect of a local thickening of the laminar boundary layer. D. G. Hurley. A.R.L./A.*146 (*July* 1955).

A simple approximate method of calculating the downstream effect of a local thickening of a laminar boundary layer is given. It is shown that the thickening dies away very rapidly in a favourable pressure gradient, but is magnified by an adverse pressure gradient. This confirms a conclusion that was drawn from experiments on the effects of surface roughness on the stalling characteristics of a thin wing.—(1.1.1.1).

Effects of sweep and angle of attack on boundary-layer transition on wings at Mach number 4·04. *R. W. Dunning and E. F. Ulmann. N.A.C.A. T.N.* 3473 (*August* 1955).

Wind-tunnel tests were conducted at Mach number 4·04 to determine the effects of leading-edge sweep, angle of attack, and leading-edge thickness on the boundary layer transition on flat-plate wings. In addition, some results were obtained on wings having rounded leading-edge sections. Transition points were determined for angles of attack up to 20° and for leading-edge sweep angles from 0° to 72°.—(1.1.2.4).

Measurements of turbulent skin friction on a flat plate at transonic speeds. R. J. Hakkinen. N.A.C.A. T.N. 3486 (*September* 1955).

The design and construction of a floating element skin friction balance are described. This instrument was applied to measurements of local skin friction in the turbulent boundary layer of a smooth flat plate at high subsonic Mach numbers and supersonic Mach numbers up to 1·75. The principal difficulties which exist in comparing skin friction coefficients at various Mach numbers are discussed.—(1.1.2).

Contributions on the mechanics of boundary-layer transition. G. B. Schubauer and P. S. Klebanoff. N.A.C.A. T.N. 3489 (*September* 1955).

The manner in which flow in a boundary layer becomes turbulent was investigated on a flat plate at wind speeds generally below 100 feet per second. Hot-wire techniques were used, and many of the results are derived from oscillograms of velocity fluctuations in the transition region. The more familiar aspects of transition are discussed, and the facts discovered while studying the characteristics of artificially produced turbulent spots are presented.—(1.1.2).

Variation of boundary-layer transition with heat transfer on two bodies of revolution at a Mach number of 3·12. *J. R. Jack and N. S. Diaconis. N.A.C.A. T.N.* 3562 (*September* 1955).

Cooling a cone-cylinder model to a wall-to-free-stream ratio of approximately 1·4 increased the transition Reynolds number from a value of $2{\cdot}0 \times 10^6$ at equilibrium to $10{\cdot}6 \times 10^6$. For temperature ratios less than 1·4, the boundary layer flow was entirely laminar. For a parabolic-nosed body, the transition Reynolds number was about twice that of the cone-cylinder model over the temperature range investigated.—(1.1.2).

Compressible Flow

Zero-lift drag of full and half-models of a body of revolution at M 1·6. *J. A. Van Der Bliek. N.A.E. Laboratory report LR-*139 (*May* 1955).

The zero-lift drag of full and half-models of a body of revolution was measured in the N.A.E. 10×10 inch and the 30×16 inch wind tunnels at $M = 1{\cdot}6$ and $Re = 2{\cdot}8$ to 6 million. Different methods of boundary layer flow visualisation and artificial transition were utilised. With a half-model the effect of tunnel wall boundary layer shim thickness was investigated.—(1.2.3).

A study of hypersonic small-disturbance theory. M. D. Van Dyke. N.A.C.A. Report 1194 (1954).

The small-disturbance equations are derived for inviscid flow past thin bodies at high supersonic speeds. Reinterpreted, they apply throughout the supersonic range. The theory is used to find pressures on cones and wedges, initial gradients on ogives, and initial pressure curvatures on ogives of revolution. Additional approximations from existing theories are discussed.—(1.2.3).

On boattail bodies of revolution having minimum wave drag. K. C. Harder and C. Renneman, Jr. N.A.C.A. T.N. 3478 (*August* 1955).

The problem of determining the shape of slender boat-tail bodies of revolution for minimum wave drag has been reexamined. It was found that minimum solutions for Ward's slender-body drag equation can exist only for the restricted class of bodies for which the rate of change of cross-sectional area at the base is zero. To eliminate this restriction, certain higher order terms must be retained in the drag equation and isoperimetric relations. The minimum problem for the isoperimetric conditions of given length, volume, and base area is treated as an example.—(1.2.3).

Control Surfaces

Pressure distributions illustrating flow reattachment behind a forward mounted flap. E. C. Maskell. A.R.C. C.P. No. 211 (*March* 1954, *published* 1955).

A series of pressure distributions over a N.A.C.A.0015 wing with a forward mounted 5 per cent chord split flap are presented. The results, obtained by Clarke in 1946, have not previously been published.—(1.3.4).

Fluid Dynamics

See also Wings and Aerofoils

Mouvement oscillatoire avec viscosité et inertie. Claire Clarion. Publications S. & T. No. 303 (1955).—(1.4).

Internal Flow

See also Thermodynamics: Heat Transfer

Rotating-stall characteristics of a rotor with high hub-tip radius ratio. E. L. Costilow and M. C. Huppert. N.A.C.A. T.N. 3518 (*August* 1955).

The rotating-stall characteristics of a 0·9 hub-tip ratio rotor are investigated. The test set-up approximates the two-dimensional model upon which recent theories have been based. Measurements of pressure, temperature, and flow fluctuations during stalled operation are reported. Experimental stall-propagation rates are compared with those predicted by theory.—(1.5.2.1).

Loads

*Aerodynamic force on an airfoil in a moving gust. A generalization of the two-dimensional gust problem. J. W. Miles. Douglas Report No. SM-*18598 (*October* 1954).

The blades of a helicopter can meet a gust that moves across the aerofoil section at a relative velocity different from the blade velocity. The increment of lift due to a sharp edge gust that moves across a two-dimensional aerofoil at a relative velocity different from the flight velocity is calculated on the assumption of incompressible flow.—(1.6.3).

Supersonic flow past oscillating airfoils including nonlinear thickness effects. M. D. Van Dyke. N.A.C.A. Report 1183 (1954).

A solution to second order in thickness is derived for harmonically oscillating two-dimensional aerofoils in supersonic flow. For slow oscillations of an arbitrary profile,

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

the result is found as a series including the third power of frequency. For arbitrary frequencies, the method of solution for any specific profile is indicated, and the explicit solution derived for a single wedge.—(1.6.3 × 2.0).

PERFORMANCE ESTIMATION

Theoretical investigation of the drag of generalized aircraft configurations in supersonic flow. E. W. Graham et al. Douglas Report No. SM-19181 (July 1955).

It seems possible that, in supersonic flight, unconventional arrangements of wings and bodies may offer advantages in the form of drag reduction. It is the purpose of this report to consider the methods for determining the pressure drag for such unconventional configurations, and to consider a few of the possibilities for drag reduction in highly idealised aircraft.—(1.7).

Friction study of aircraft tire material on concrete. W. G. Hample. N.A.C.A. T.N. 3294 (September 1955).

A systematic study was made of the variation of frictional resistance between typical tyre tread material and three concrete surfaces of different roughness at various temperatures and normal pressures. The tyre tread specimens were taken from the thickest portion of worn ten-ply tyres, and the three concrete test blocks were poured from the same mix but subjected to different surface finishes. Curves are presented of the apparent coefficient of friction as a function of normal pressure.—(1.7 × 4.2.2.3).

STABILITY AND CONTROL

Manoeuvrability of aircraft in circling flight. H. L. Price. R. & M. No. 2838 (May 1952, published 1955).

An investigation is made into the manoeuvre of an aeroplane in the entry into and recovery from a true banked horizontal turn executed without sideslip or loss of height, and the proper continuous co-ordination of aileron, elevator and rudder is deduced for all stages of the manoeuvre. It is shown that the rolling motion is practically unaffected by the other modes of motion, enabling the kinematics of the rolling mode to be solved in terms solely of the applied aileron movement or stick force. The aileron is regarded as the prime initiator of the turn, operated in some prechosen manner, and the elevator and rudder loads are expressed as functions of the determinable rolling velocity and acceleration. The loads to trim in the final steady turn are found as a particular case.—(1.8.1).

On the use of the indicial function concept in the analysis of unsteady motions of wing and wing-tail combinations. M. Tobak. N.A.C.A. Report 1188 (1954).

The concept of indicial aerodynamic functions is applied to the analysis of the short-period pitching mode of aircraft. By the use of simple physical relationships associated with the indicial-function concept, qualitative studies are made of the separate effects on the damping in pitch of changes in Mach number, aspect ratio, plan form, shape, and frequency.—(1.8.2.2).

A study of the characteristics of human-pilot control response to simulated aircraft lateral motions. D. C. Cheatham. N.A.C.A. Report 1197 (1954).

There are presented studies of the characteristics of pilot ability to control dynamically unstable yawing oscillations, studies of pilot control response to simulated aircraft yawing motions, and studies of the feasibility of representing pilot control response in an analytical form.—(1.8.1).

Free-spinning-tunnel investigation of gyroscopic effects of jet-engine rotating parts (or of rotating propellers) on spin and spin recovery. J. S. Bowman, Jr. N.A.C.A. T.N. 3480 (August 1955).

A rotating flywheel powered by a model aeroplane engine mounted on a model in the Langley 20-foot free-spinning tunnel was used to simulate the gyroscopic effects of jet-engine rotating parts (or of rotating propellers) on the erect spin and spin-recovery characteristics of a military attack aeroplane.—(1.8.3).

Comparison of the measured and predicted lateral oscillatory characteristics of a 35° swept-wing fighter airplane. W. E. McNeill and G. E. Cooper. N.A.C.A. T.N. 3521 (August 1955).

Flight measurements of the lateral oscillatory characteristics were obtained at altitudes of 10,000 and 35,000 feet for an overall Mach number range from 0·41 to 1·04. Period, time to damp to half amplitude, and ratio of angle-of-bank amplitude to angle-of-sideslip amplitude, $|\phi|/|\beta|$, are presented as functions of Mach number for each test altitude, and are compared with values computed from wind-tunnel data and estimated stability derivatives.—(1.8.1).

Effectiveness of wing vortex generators in improving the maneuvring characteristics of a swept-wing airplane at transonic speeds. N. M. McFadden et al. N.A.C.A. T.N. 3523 (September 1955).

The effects of wing vortex generators, multiple boundary layer fences, and extension of the outer two segments of the wing leading-edge slats on the aerodynamic characteristics of a 35° swept-wing fighter were measured in flight tests at transonic speeds and high altitudes. Significant improvements were obtained in the pitch-up and wing-dropping-tendency characteristics with certain arrangements of vortex generators.—(1.8).

WINGS AND AEROFOILS

Drag of superimposed optimum lift distributions in supersonic flow. E. W. Graham. Douglas Report No. SM-18839 (April 1955).

The methods considered apply to the theoretical evaluation and reduction of aircraft wave and vortex drag in supersonic flight. Linearised theory is used, and the aircraft is assumed to be represented by the super-position of several elementary distributions of lift and thickness whose properties (individual lifts or volumes and drags) are known. It is then necessary to determine the interference drag among these elementary loadings in order to determine the total drag of the combination.—(1.10.2.2).

Drag due to lift in supersonic flight for circular planform wing with an arbitrary radial distribution of lift. R. M. Licher. Douglas Report No. SM-19119 (June 1955).

The ideas of Graham regarding the calculation of the interference drag between certain "optimum" distributions of lift are used to show how the drag of any arbitrary lift distribution may be represented in terms of the drag of an infinite set of optimums. This is demonstrated for the special case of a circular plan form wing having a distribution of lift that varies only in the radial direction.—(1.10.2.2).

Reduction of profile drag at supersonic velocities by the use of airfoil sections having a blunt trailing edge. D. R. Chapman. N.A.C.A. T.N. 3503 (September 1955).

A preliminary theoretical and experimental investigation has been made on the aerodynamic characteristics of blunt trailing edge aerofoils at supersonic velocities. The theoretical considerations indicate that properly designed aerofoils with moderately blunt trailing edges can have less profile drag, greater lift-curve slope, and a higher maximum lift-drag ratio than conventional sections.—(1.10.2.1).

An experimental investigation of regions of separated laminar flow. D. E. Gault. N.A.C.A. T.N. 3505 (September 1955).

Results are given for an experimental investigation of regions of separated flow initiated by separation of the laminar boundary layer (laminar separation "bubbles"). Total- and static-pressure surveys, hot-wire anemometer observations, and detailed pressure-distribution measurements were made in regions of separated flow on two aerofoils. The measurements were obtained for a wide range of angles of attack and for Reynolds numbers from 1·5 to 10 million. Some results on the effects of an increase in turbulence level of the free stream are also included.—(1.10.2.1 × 1.4).